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Ecological Research Associates

**IMPORTANCE OF THE EASTERN ALASKAN BEAUFORT SEA  
TO FEEDING BOWHEAD WHALES, 1985-86**

by

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## ABSTRACT

The general purpose of this two-year project was to quantify what proportion of the **annual** energy requirements of the Western Arctic **bowhead whale** stock is **provided by** food resources located in the Eastern Alaskan **Beaufort Sea (Alaska/Canada border to 144°W)**. Specific objectives were to

1. Determine **the concentration** and distribution of the **planktonic** food of bowhead whales in **the Eastern Alaskan Beaufort Sea** and correlate with known oceanographic features.
2. Estimate **the number of bowhead whales** utilizing the Eastern Alaskan **Beaufort Sea** as a feeding area **during** the summer and **fall**; observe and document their feeding **activities**, behavior and residence times.
3. Estimate the degree of utilization of available food resources **in** the Eastern Alaskan Beaufort Sea **by** the Western Arctic bowhead **whale** stock\*

This final report is an integrated account of fieldwork done in September and early October of 1985-86, along with previously available data.

Water masses in the study area were studied by boat-based sampling and by airborne and satellite remote sensing. After periods of easterly winds, water masses include (1) a nearshore band of relatively warm water, (2) an area of cold, high-salinity water over the inner shelf, with strong evidence of upwelling, and (3) an area of warmer, fresher, more turbid water (of Mackenzie Bay origin) near and beyond the shelf break. After periods of west winds, the water is more homogeneous, with no coastal upwelling and less influence of the warm Mackenzie Bay water. Fronts and eddies were detected at several locations. In some years, including 1986, a subsurface mass of Bering Sea water moves east into the study area near the shelf break.

Zooplankton composition, biomass, distribution, patchiness, and energy content in September of both 1985 and 1986 were documented by boat-based sampling from the nearshore zone out to the 200 m contour, In 1986, additional samples were obtained across the full width of the Alaskan Beaufort Sea during October, and near feeding bowhead whales in September. Most net sampling was done with oblique bongo tows and by horizontal tows in plankton layers identified by echosounding. Also, quantitative echosounding techniques, calibrated by the bongo sampling, were used. Maximum zooplankton biomass generally was in one or more thin layers in the 8-40 m depth zone. Biomass was usually low in near-surface waters, and decreased with increasing distance from shore. Copepods dominated the biomass. The highest biomasses of zooplankton, mainly the small copepod Limnocalanus macrurus, were found near bowhead whales feeding in nearshore waters in early September 1986.

The distribution, numbers and activities of bowhead whales were determined by aerial surveys and behavioral observations from the aircraft. Photogrammetric methods were used to document whale sizes and the recurrence of identifiable individuals in feeding areas. Five bowheads were radio-tagged in 1986. Unusually few bowheads fed in the study area in late summer and autumn of 1985; 1986 was a more typical year. Prior to the onset of westward

migration, very few bowheads were in the study area in 1985, but about **50 subadult** bowheads fed in nearshore waters **at** the SE corner of the study area **in** 1986. **In** both years, numerous **subadult** bowheads fed along **the** Yukon shore just east of the official study area in **late** August and September; some recognizable individuals were there for at least 16 days. After active migration began in mid September, adult and large **subadult** whales fed in the middle-shelf portion of the study area in both years.

Analyses of carbon isotope ratios in **zooplankton** and bowhead tissues suggested that a significant amount of feeding is done outside the eastern **Beaufort Sea**, at least by subadult **bowheads**. Annual oscillations in isotope content along the baleen were documented; these provide data on age **and** feeding history. Bowheads apparently grow **slower** than previously believed.

The Western Arctic population of bowheads acquired a low percentage of its total **annual** food and energy needs within the study area--probably <1% **in** 1985 and perhaps about 1.4% in 1986. In many parts of the study area, **zooplankton** biomass was too low for efficient feeding. However, **zooplankton** biomasses **in** the nearshore feeding area studied in 1986 were similar to those where bowheads feed in the Canadian **Beaufort** Sea. Although most individual whales acquired **little** of their **annual** energy intake in the study area in 1985-86, many (if not all) did feed there briefly while migrating west. **In** years like 1986, a minority of **the** individual bowheads remain **in** the Eastern Alaskan Beaufort Sea **long** enough to acquire a significant **amount** of food.

## PROJECT ORGANIZATION AND ACKNOWLEDGMENTS

This report describes fieldwork conducted by LGL during September-October of 1985 and 1986, with assistance from subcontractors BioSonics Inc. (hydroacoustics), G.A. Borstad Associates Ltd. (airborne remote sensing), and University of Alaska (calorimetry, isotopic analyses). Additional subcontractors that participated in the analytical work were Arctic Sciences Ltd. (physical oceanography, satellite remote sensing) and Greeneridge Sciences Inc. (underwater acoustics). This report is an integrated account of the results from both years of the study. Additional details about the 1985 phase are given in Richardson (cd., 1986).

This report was prepared by

- W.B. Griffiths, G.W. Miller, W.J. Richardson, and D.H. Thomson of LGL Ltd.; and D.R. Schmidt of LGL Alaska;
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## EXECUTIVE SUMMARY

Most members of the Western Arctic population of bowhead whales migrate through the Alaskan Beaufort Sea during September and October while en route from the main summer feeding grounds in the Canadian Beaufort Sea to the wintering grounds in the Bering Sea. Some feeding occurs within the Alaskan Beaufort Sea during late summer and early autumn. It has been hypothesized that this late summer feeding may be especially important to bowheads because they may not feed again for several months after leaving the Beaufort Sea, and because the energy content of arctic zooplankton is high in late summer.

To evaluate the possible effects of offshore oil exploration in the Eastern Alaskan Beaufort Sea on bowhead whales, regulatory agencies considered it necessary to evaluate the importance of the area to feeding bowheads. A contract for a two-year field study of this question was awarded in 1985 by the U.S. Minerals Management Service to LGL Ecological Research Associates. The general purpose of the project was to quantify what proportion of the annual energy requirements of the Western Arctic bowhead whale stock is provided by food resources located in the Eastern Alaskan Beaufort Sea (Alaska/Canada border to 144°W). Specific objectives were to

1. Determine the concentration and distribution of the planktonic food of bowhead whales in the Eastern Alaskan Beaufort Sea and correlate with known oceanographic features.
- 2\* Estimate the number of bowhead whales utilizing the Eastern Alaskan Beaufort Sea as a feeding area during the summer and fall; observe and document their feeding activities, behavior and residence times.
3. Estimate the degree of utilization of available food resources in the Eastern Alaskan Beaufort Sea by the Western Arctic bowhead whale stock.

The report describes results of fieldwork in September and early October of 1985 and 1986. A review of published and unpublished information was done before the first field season; results of that review are also taken into account.

Water Mass Distributions

Zooplankton availability was expected to be strongly related to physical oceanographic factors. Consequently, it was necessary to study the water masses within the study area at the times when zooplankton and feeding whales were studied. Water masses were studied by boat-based CTD and surface sampling, and by airborne and satellite remote sensing.

Water masses in the study area can vary considerably from year to year, and within years. The variability results from the peripheral location of the study area relative to the sources of water masses originating in the Mackenzie Bay area and in the Bering-Chukchi Sea region.

The water column consists of three reasonably distinct zones: an upper **layer**, the **pycnocline**, and a lower layer. In the upper layer, extending from the surface to depths of 4-12 m, there is **little vertical** change in temperature, salinity or density. However, temperature and salinity vary considerably with location and time. The main **pycnocline** extends from the bottom of the upper layer down to 15-32 m. Salinity and density increase and temperature decreases with increasing depth. The **lower** layer, extending from the **pycnocline** to the sea bottom, has comparatively weak vertical gradients in salinity and density, although there can be **large** temperature changes.

The characteristics of the lower **layer** differed between years. In September 1985, the lower layer consisted exclusively of **cold**, saline Arctic Surface Water (**ASW**), which originates at depths of 0-200 m in the Arctic Ocean proper. In September 1986, ASW again formed part or all of the **lower layer** in many areas. However, in 1986 a very prominent subsurface core of much warmer Bering Sea Water (**BSW**) was present over the outer continental **shelf and** continental **slope**. Maximum temperatures of **3-4°C** were observed. The occurrence of BSW within the study area is apparently rare, based on the limited previous data from this area.

Within the **pycnocline**, water mass types were either (a) a mixture of the deeper ASW with the overlying upper layer; or (b) Cold **Halocline** Water (**CHW**). CHW originates as a mixture of ASW with the **cold**, fresh upper **layer present** during seasonal ice melt. **CHW** occurred most frequently in the western offshore portion of the study area.

The influence of the massive freshwater outflow from the Mackenzie River extends into the Eastern Alaskan study area to varying degrees. Warm, **fresh**, turbid water of Mackenzie Bay origin was often present in the upper layer over the offshore portion of the study area, from the edge of the continental **shelf to** abyssal depths. The influence of this Mackenzie plume was especially prominent in early September 1985 as a **result** of an extended period of east winds and heavy ice conditions east of the Mackenzie **Delta**.

Over the continental shelf inshore of the Mackenzie plume, the surface layer over the middle and inner **shelf** differed from that closer to shore in the nearshore zone. The nearshore **water** mass showed strong **estuarine influence**. It occurred as a **thin**, narrow discontinuous band of turbid water **along** the coast in both 1985 and 1986. The **areal extent** of this water type was **larger** in 1986 than 1985. Beneath the thin surface **layer**, cold **saline** Arctic Water was found within 5-15 m of the surface. Over most of the continental shelf between the nearshore zone and the Mackenzie plume, the upper **layer** was characterized by cold (**<1.5-2.5°C**) saline Arctic water. In 1986, this **cold** surface water over the inner and **middle shelf** was generally confined to areas west of **142°W**; the upper **layer** over the eastern portions of the inner and middle shelf was much warmer (**2.5-5.0°C**).

**CTD** and nutrient data provided strong evidence of coastal **upwelling** in the inner shelf zone during the 5-10 **September 1985** period, but 'not in the 10-19 September 1986 period. This difference was to be expected, given the more consistent easterly winds in 1985.

The distribution of water masses and sea-ice changed markedly in mid-late September of both 1985 and 1986, as a **result of** strong northwest or west winds. Following the strong winds, water of Mackenzie Bay origin was no longer identifiable in the Eastern Alaskan Beaufort Sea. High levels of vertical mixing had resulted in **cooler**, more **saline**, and more homogeneous surface water. Northwest winds in mid-September 1985 brought much ice into the study area; west winds in 1986 had much less effect on ice.

Large **scale** fronts occur in most years within the study area. One front occurs **along** the inshore side of the **warm**, less **saline** Mackenzie Bay water near the shelf break. This front is strongest in the eastern part of the study area. Another front separates turbid nearshore waters from cooler and clearer inner shelf waters. Other large scale fronts were more **ephemeral**, differing considerably between 1985 and 1986. Airborne and satellite remote sensing suggested that meanders and eddies, likely of offshore origin, were present within the **cold**, saline surface waters over the inner shelf. Typical diameters, as resolved in satellite imagery, ranged up to 10-15 km. Intense fronts over spatial scales as small as a few hundred meters were detected by higher resolution sampling from the aircraft and boat.

### Zooplankton and Hydroacoustics

Zooplankton composition, biomass, distribution, patchiness, and energy content were documented by boat-based sampling **along** broad-scale transects **extending** from shore to about the 200 m contour. We completed  $2\frac{1}{2}$  of these transects in 1985 and 4 in 1986. At 2-5 stations **along** each transect, zooplankton was sampled by oblique bongo tows and by horizontal tows guided to plankton layers by echosounder. At some stations and depths in 1985, paired bongo tows and Tucker trawls were performed to confirm the effectiveness of bongo tows in capturing large, fast-moving zooplankters. In addition, quantitative echosounding techniques were used to determine the vertical distribution of zooplankton along the full length of all transects. The raw echosounder results were converted to estimates of actual zooplankton biomass based on the relationship between echosounding and net sampling at locations where both were done. In October 1986, additional icebreaker-based sampling was done across the entire Alaskan Beaufort Sea (Barrow-Canadian border, 40-2000 m contour) to compare zooplankton in the main study area with that farther west and north.

The intention in both years was to conduct broad-scale zooplankton sampling **early** in **September**, and to conduct fine-scale sampling near feeding bowheads when and if the boat could reach feeding areas. In fact, bowheads did not feed in the official study area during early-mid September 1985, and ice prevented sampling near bowheads in late September 1985. In 1986 feeding bowheads were present in the southeast part of the study area during early September, and fine-scale sampling was done near five groups of feeding bowheads before broad-scale sampling commenced.

The group and species composition of the zooplankton in the Eastern Alaskan Beaufort Sea was similar to that elsewhere **along** the Beaufort Sea coast and in other arctic regions. However, relative abundances of some species and groups vary between locations and years. Copepods dominated the zooplankton along the broad-scale transects during September 1985-86,

representing 78 and 81% of the wet weight, respectively, and 87 and 98% of the individual **zooplankters**. In October 1986, **copepods** accounted for 85% of the individuals but only 24% of the biomass in the upper 50 m of the water column over the mid-shelf and continental slope in our main study area."

In September 1985, the large (>1.8 mm in length) copepods **Calanus hyperboreus** and **C. glacialis** were the dominant contributors to **total zooplankton** biomass, while in September 1986 the small (<1.8 mm in length) copepod **Limnocalanus macrurus** was the dominant contributor. In both years, **Limnocalanus** dominated in nearshore waters and **Calanus** dominated farther offshore; the zone with abundant **Limnocalanus** was more extensive in 1986. In both years, **euphausiids** and **mysids** were most abundant near the bottom in nearshore waters. Whether they also occurred in similar abundances near the bottom farther offshore is not certain, since few near-bottom samples were taken offshore. In October 1986, euphausiids were much more abundant farther west, between Pt. Barrow and Prudhoe Bay, than in the official study area.

In September 1985-86, average **zooplankton** biomass was highest in the nearshore and inner shelf areas (south of the 50 m contour), and lower on the outer shelf (north of the 50 m contour). Biomass in the intrusion of Bering Sea Water over the outer shelf in 1986 was unremarkable. Biomass in the top 50 m over the continental slope (near 1800 m contour) was similar to that over the outer shelf, and much higher than previously reported for the top 200 m of the Arctic Ocean far offshore. Average **zooplankton** biomass in the top 50 m within our study area was similar in both years, about 200 mg/m<sup>3</sup> (wet weight). Our average biomasses were similar to those over the continental shelf of the Canadian Beaufort Sea during late August and early September 1985-86 (cf. Bradstreet et al. 1987).

Hydroacoustic surveys showed that zooplankton distribution was patchy in both years. Patches tended to be more abundant in nearshore and inner shelf waters (<45 m deep) than over the outer shelf. Average **zooplankton** biomass within patches was also higher in nearshore and inner shelf areas than farther offshore. Zooplankton patches often extended for several kilometers in the horizontal plane, but usually were only 5-10 m thick. Patches along broad-scale transects were typically more extensive in the horizontal plane in September 1985 than in September 1986.

Feeding bowheads were present in nearshore waters in the SE corner of the study area (and to the east along the Yukon coast) in early September 1986. In 1986, average **zooplankton** biomass was higher at five whale feeding stations than at corresponding control stations. Average biomass at our whale feeding stations was similar to that at whale feeding stations farther east along the Yukon coast (cf. Bradstreet et al. 1987). Bowheads usually feed in areas where **zooplankton** biomass is about 1-3 g/m<sup>3</sup> at the depth of maximum biomass (mean 2 g/m<sup>3</sup>). In all cases the higher **zooplankton** biomass at our whale feeding stations was due to unusually high **copepod** biomass. The biomass of all other **zooplankters** combined was similar at whale feeding and control stations. Although major efforts were made to minimize the various biases normally associated with **zooplankton** sampling, 2 g/m<sup>3</sup> is probably an underestimate of mean biomass in the water filtered by bowheads.



Limnocalanus macrurus was the dominant copepod at whale feeding locations along both the Alaskan and the Yukon coasts. These small copepods, <2 mm in length, can be filtered from the water by bowhead whales; L. macrurus was a major food item in the stomach of one bowhead taken near Kaktovik in September 1986.

Although dense layers of concentrated zooplankton were most common in nearshore waters, especially near feeding bowheads, such layers did occur farther offshore over the continental shelf. Other taxa, usually Calanus, dominated in these patches. Although these patches were not being used by feeding bowheads during our zooplankton sampling periods, they presumably are used at other times.

In September 1985-86, zooplankton biomass was very low in surface and near-surface waters. The majority of zooplankters were between the pycnocline and a depth of 45 m, except at some nearshore 'stations where the pycnocline layer was continuous from a few meters depth to the bottom. Most zooplankters were in one or more layers a few meters thick at mid-water or near-bottom positions. This was true at whale feeding and control stations as well as along broad-scale transects, Consistent with this, almost all whales observed feeding in the official study area fed in the water column, below the surface.

In September 1985, zooplankton biomass was slightly higher within than outside frontal areas. In September 1986, we found no such trend. However, the subsurface concentrations of zooplankton in nearshore feeding areas were in cold saline waters overlain by much warmer turbid water, and inshore of areas where subsurface waters were slightly warmer and less saline.

Copepods had a higher energy content per unit weight than other major groups. Copepods contributed 90 and 89% of the total caloric content of the zooplankton in 1985 and 1986, respectively. Caloric content per gram of zooplankton was higher in 1985 than in 1986, and higher in our study area than in the Canadian Beaufort Sea about two weeks earlier. Along broad scale transects, mean caloric content of the zooplankton in the top 50 m, on a 'per cubic meter' basis, was similar in 1985 and 1986: 225 vs. 179 cal/m<sup>3</sup>, respectively. At whale feeding stations, mean caloric content was much higher, 643 cal/m<sup>3</sup> in the water column as a whole and 2132 cal/m<sup>3</sup> in concentrated layers of zooplankton.

#### Bowhead Distribution, Numbers and Activities

The distribution, numbers and activities of bowheads were determined by aerial surveys and behavioral observations from the aircraft. Photogrammetric methods were used to document whale sizes and recurrence of identifiable individuals in feeding areas. Our observations were mainly in September, but supplementary data were obtained from other studies before and after our field periods. In 1986 we radio tagged five bowheads in. a further attempt to document behavior and residence times at feeding areas.

A few bowheads were seen in the Eastern Alaskan study area by other investigators during August 1985-86, most over the outer continental shelf and continental slope near the eastern edge of the study area. Bowheads fed along

the Yukon coast just east of the study area in August of both years, but these **whales** did not extend into Alaskan waters in August.

The 1985 migration through the study area began around 11 September, and apparently peaked in late September after much ice was blown into the study area. At least some of the whales migrating through mid-shelf waters in **late** September fed briefly. Some bowheads continued to travel west through the study area, in heavy ice conditions, during **early** to mid October 1985.

More whales were in the study area during early-mid September in 1986 than in 1985, including a concentration of feeding whales close to shore **off the Kongakut Delta** in the southeast corner of the **study** area. The latter area was the westernmost of several feeding locations **along** the Yukon and **Alaskan** coast. Westward migration began **in** early September 1986, and probably peaked in **late** September. Migrating whales were **closer** to shore in mid- and late September than in early September. Migration continued into October 1986, after our fieldwork ended.

In 1985, raw density estimates from aerial surveys of the continental shelf and **slope** zones were very **low**, only about 0.06 and **0.04 bowheads/100 km<sup>2</sup>**, respectively, during mid-late September. These figures are very approximate because of the low number of sightings. **In** 1986, estimated densities in the shelf zone during September (excluding the feeding area off the **Kongakut Delta**) were considerably higher, ranging from **0.21** to 0.33 **bowheads/100 km<sup>2</sup>**; the **estimated** raw density over the continental **slope** was **0.12 bowheads/100 km<sup>2</sup>** in early "September, but zero thereafter. Limited coverage of the northern part of **the** study area (depths **>2000 m**), **mainly by** the Naval Ocean **Systems** Center, revealed no bowheads in either year; a few bowheads have been seen there in earlier years.

Behavioral data indicated that **only** about 12-14% of the **bowheads** present '**on-transect**' were potentially detectable during standard aerial surveys; **whales** were submerged and invisible **almost** 90% of the time. Available data from **1981-84 suggest** that detectability of bowheads **in** and near our **study** area was similarly **low** in those years. Detectability was apparently even **lower** for whales in areas of heavy ice-covers e.g. in **late** September 1985.

Even **after** allowance for the many whales present but undetectable during **aerial** surveys, numbers **in** the study area in **1985** were very **low**, estimated as **<100**, at **all** times during late summer and **early autumn**. Higher numbers, estimated **as** 220-370, were present at various times **in** September 1986. Utilization of the study area in August-October was estimated as about 4200 whale-days in 1985 and 13,000 whale-days **in** 1986. The **1985** value may be an underestimate given that it is **barely** adequate **to** account for steady westward **migration** of a population of **4417** whales across the study area, and inadequate **if** the population size is about 7200 as is now suspected.

Mother-calf pairs sighted within the study area during 1985-86 were widely distributed geographically and temporally, as in previous years.

Many feeding bowheads lingered along the Yukon coast near Komakuk, **10-50** km east of the official study area, during **late** August and much of September 1985-86. Several recognizable whales photographed near **Komakuk** were

rephotographed on **later** days and/or the next year. Within years, minimum residence times averaged 7.6 d ( $n = 11$ ), with a maximum documented period of **16 d**. Most **bowheads** in this nearshore area were **subadults** 7-13 m long, but a few **adults** were present. We **radiotagged** five bowheads in this area in 1986; **three** were detected on subsequent days after they **had** begun migrating west through Alaskan waters.

The **concentration** of feeding whales near the **Kongakut Delta**, in the official **study** area, during **early** September 1986 was apparently a westward extension of the nearshore concentration farther **east**. Again, most whales were **subadults**. Six individuals were rephotographed 1-2 d after first being photographed, but the overall duration of feeding off the **Kongakut Delta** was briefer than that along the coast farther east.

Late September was the only time in 1985 when a concentration of feeding **bowheads** was found within the study area. They fed about 30-40 km N and NE of **Kaktovik**. Similarly, many whales that were migrating through middle shelf waters in mid-late September 1986 fed intermittently. In both years, **whales** that fed over the middle shelf during migration included many **adults** (some with calves) as well as **large subadults**, but few **small** (<10 m) **subadults**. These **whales** did not seem to **linger** in any one area for long; there were no between-day reidentification at middle-shelf feeding sites. However, several of these whales had been **photographed** earlier in the **season** (or in previous summers) in Canadian waters.

The behavior of **bowheads** feeding within and near the study area was similar to that documented during previous studies in summer and early autumn. Most bowheads feeding within the official study area fed below the surface, consistent with the **low** abundance of **zooplankton** in surface waters. In contrast, bowheads often fed at the surface along the Yukon coast. Almost no near-bottom feeding was detected. Many of the bowheads observed within and just east of the official study area during 1985, and to a lesser extent 1986, were exposed to faint-moderate intensity noise **pulses** from distant seismic vessels. Activities seemed **normal** despite this noise exposure. When bowheads engaged in presumed water column feeding, net horizontal distances travelled during single dives ranged from about 0 to 700 m, averaging about 300 m during dives of average duration 15 min. Actual distances travelled underwater were undoubtedly greater, thereby increasing the potential volume of water filtered. During some observation sessions when bowheads were feeding, the headings of the **whales** when they surfaced to breathe were predominantly westward. This suggests that bowheads sometimes were migrating gradually westward as they fed.

Observed feeding locations in and near the Eastern Alaskan Beaufort Sea have differed between years. No one part of the **study** area has been identified as a consistent feeding location. The study area is apparently near the western edge of the main summer feeding **range**. Prior to the **start** of active westward migration, feeding whales extend into the study area in some years (like 1986) but not in **all** years. During the subsequent period of active westward migration, considerable feeding takes **place** in the study area, probably in **all** years. Utilization of the study area for feeding was less than average in 1985. Utilization was considerably greater in 1986 than in 1985, but apparently not as high as in some other years.

Bowhead Whale Feeding: Allocation of Regional Habitat Importance  
Based on Stable Isotope Abundances

The **goal** of the isotope work was to use the variations in **natural** abundances of carbon isotopes in zooplankton and in bowhead whale tissue to estimate the relative importances of various feeding areas, with emphasis on estimating the amount **of** feeding in winter. **In** addition, the discovery **of** regular variations in carbon isotope ratios along bowhead **baleen** has provided a potential method for ageing young whales, which may provide insights into **life** history. We analyzed baleen **and/or** tissue samples from 16 whales during this **project**, ranging from yearlings to large adult animals. Muscle, blubber and baleen from several other bowheads had been analyzed previously.

The ratio of **stable carbon** isotopes (**C-13/C-12**) in zooplankton varied across the range of **bowhead** whales. **C-13** was more common in **zooplankton** from the western Beaufort Sea and (probably) northern Bering Sea than **in zooplankton** from the central and eastern Beaufort Sea. As expected, there was proportionately **less C-13** in primary consumers (e.g. **copepods**) than in omnivores or secondary consumers (e.g. euphausiids, **chaetognaths**, **amphipods**).

In young **bowheads**, the muscle and visceral fat contained relatively more C-13 in spring than **in** autumn. If our **small** samples were representative, young **whales** acquire a significant fraction of their **annual** food intake during the **late** autumn-winter-early spring period **while** they are not in the eastern or central **Beaufort** Sea.

**In large** bowheads, carbon isotope ratios in muscle **and** visceral fat were similar **in** spring and autumn. The **muscle** was enriched in C-13 in both seasons, suggesting that most of this carbon may not have come from **the SE Beaufort** Sea. The significance of these data is unclear, other than to suggest that **large whales tended** to feed in different areas and/or on different prey types **than small bowheads**.

The c-13/c-12 ratio oscillated along the baleen, with a spacing of >25 cm/oscillation early in **life**, and about 20 cm/oscillation **in adults**. **In large whales**, **up** to 20+ isotopic oscillations were present. The pattern of oscillations was consistent **along** different **baleen plates** from the same **whale**. Several types of evidence suggested that the oscillations **along** the **plates** were annual. By counting the **stable** isotope oscillations along the **baleen**, ages of young bowheads can be determined. After several years, wear at the tip of the baleen prevents precise **ageing**, although a minimum age can still **be** determined. The annual isotopic oscillations also correspond with structural patterns visible along the baleen. Data acquired incidental to our objectives showed **that**, after the age of about 1 **year**, total lengths of bowhead **whales** increase at a slower rate than suggested previously. For **example**, bowheads that are 9 m **long** appear to be several years **old**.

The carbon present at each point along a **baleen plate** is a **sample** of the carbon in the energy source in use by the **whale** when that part of the **baleen** was formed. Thus, the **baleen** provides a multi-year temporal record of feeding, representing **20+** years in large whales. The C-13-depleted **baleen** laid down in summer was consistent with the isotopic **composition** of **zooplankton** in the eastern Beaufort Sea, The C-13-enriched baleen **laid** down in winter was

qualitatively consistent with the elevated C-13 content of zooplankton in the western **Beaufort** Sea and probably the northern Bering Sea. However, the degree of C-13 enrichment in winter baleen was greater than expected based on the geographic shift in isotopic **content** of any one prey **type**. Winter baleen may incorporate carbon from omnivores or secondary consumers e.g. **euphausiids** or **amphipods**, in which **C-13** is further enriched.

The limited **data** on isotopic composition of zooplankton in the northern **Bering** Sea do **not allow** a reliable **distinction** of carbon from the western **Beaufort** Sea, **Chukchi** Sea and Bering Sea. Thus, **it is not** possible to say how much of the carbon in 'winter baleen' comes from feeding in the Bering Sea as opposed to mobilization of energy stored **during late** autumn farther north.

The baleen of most young bowheads showed a decrease in overall C-13 content in the first 6-8 years of life, accompanied by increased amplitudes of the seasonal oscillation in isotopic content. The specific causes of these changes are uncertain. The transition from dependence on mother's milk to independent feeding may be partly responsible. Other possibilities are year to year changes in feeding areas **and/or** a postulated increase in the filtration efficiency of the lengthening baleen. Either factor **could** result in a shift in the diet toward smaller prey items like copepods, which are depleted of **C-13**.

Overall, the results **suggest** that **small** bowheads acquire a significant amount of **energy** from feeding in areas west of the Eastern Alaskan **Beaufort** Sea. How **much** of this energy is acquired in winter in the Bering Sea vs. **autumn** or spring in the western **Beaufort** Sea or **Chukchi** Sea is unknown. The results from **large whales** are more difficult to interpret, **but they** may obtain much of their energy from somewhere other than the south-central and southeastern **Beaufort** Sea. Isotopic analyses of selected additional **samples** of bowhead tissue **and zooplankton** could clarify these points.

#### Energetic of Bowheads

There have been several **attempts** to calculate the **theoretical** energy requirements and feeding rates of bowhead whales. We have reviewed these **attempts** and have prepared **updated** estimates based on **current** knowledge of bowhead sizes, length-weight relationships, physiology, **growth rates**, population composition and other factors. Energy requirements of bowhead whales are still somewhat uncertain. However, the **apparent** energy needs of **bowheads** are generally consistent with what is known about other **large** whales. **Also**, most of the different methods for calculating energy needs give similar results. Food requirements and food availability can be estimated with sufficient accuracy to warrant comparison.

One **uncertainty** affecting the energetic analysis has been the unknown **amount** of feeding in winter and during migration around western **Alaska**. The carbon isotope results suggest **that** there may be a significant amount of feeding outside the Beaufort Sea, **at least** by **subadults** (see above). **Thus**, most of our calculations assume a high feeding rate for 130 d in summer and early autumn, and a lower feeding rate (30% of **daily** maintenance rate) for the rest of the year. Other feeding scenarios are also considered.

The **annual** food requirement for a population of 4417 **bowheads** is estimated to **be** about 421,000 **MT** (metric tons), with **broad** confidence limits. This value is higher than some previous estimates, primarily because **the** caloric content of **zooplankton** in the **Beaufort** Sea, on a wet weight basis, is **lower** than assumed in some previous analyses. Numerous other refinements in the estimation process are described in this report. If the population size is about 7200 whales rather than about 4417, their food requirement would **be** about 690,000 **MT/yr.**

Bowheads must feed **in** areas where the biomass of zooplankton exceeds the average biomass **in** the **Beaufort** Sea, which is about  $0.2 \text{ g/m}^3$  (**wet weight**). Theoretical calculations indicate **that** an average bowhead must feed **at** **locations** where average **zooplankton** biomass is at least  $2\frac{1}{2} \text{ g/m}^3$  if it is to acquire its annual food requirement in 130 d feeding for 16 h/d. The average prey biomass at summer feeding locations would need to be  $2 \text{ g/m}^3$  if 30% of daily maintenance requirements were met by supplementary feeding during the rest of the year. These theoretical figures are generally consistent with the observed mean **zooplankton** biomass at bowhead feeding sites ( $2 \text{ g/m}^3$  at depth of maximum biomass), especially if allowance is made for the fact that the observed values are probably underestimates of **the** food consumed by whales.

Required prey **biomasses**, on a 'per cubic meter' basis, appear to be similar for subadults and adult **males** but higher for **adult** females. This assumes that subadults grow at the **slow** rate implied by analyses of baleen. Required prey biomasses for **subadults** would be about 21% higher if they grew **at** the faster rate previously assumed. The apparent slow **growth rate** may be an adaptation to **the** relatively **low zooplankton** biomasses available **in** the Beaufort Sea.

### Integration

The 'Integration' section draws together the results from the various disciplinary sections **in** order to evaluate **the** energetic importance of the Eastern Alaskan Beaufort Sea **to** the Western **Arctic** stock of bowhead whales. This section **also** discusses "the feeding locations **that** were identified within **the** study area; feeding **in** other areas during various **seasons**; and the possible effects of industrial activities **on** feeding **bowheads**."

The **total** amount of **zooplankton** **in** the top 50 m of the water column within the Eastern Alaskan study area was **estimated** as about 150,000 **MT** in **late** summer. Of this, about 75,000 **MT** was over the continental **shelf** where most bowhead feeding occurs. **Thus**, **zooplankton** **in** the study area represented .s significance percentage of the annual population requirement of about 421,000 **MT** for 4417 bowheads. However, of the 75,000 **MT** over the continental shelf, **only** about 8100 **MT** (1985) or 1100 **MT** (1986) was, **at** any one time, in concentrations sufficiently dense to **permit** economical feeding by **bowheads**. These amounts are very **small** percentages of the **annual** population requirement.

The estimated whale-days of utilization figures for 1985 (4200 whale-d) and 1986 (13,000 whale-d) also indicate that the Western Arctic **bowhead** population acquired very **little** of its annual food requirement in the study area in those years. If these bowheads fed in water with an average of  $2 \text{ g/m}^3$  of **zooplankton** for 12 h/d at a swimming speed of 5 km/h, they would have

consumed only about 2000 MT **in 1985** and 6060 MT **in 1986**. This consumption represents only 0.5% and 1.4%, respectively, of the estimated **annual** food requirement of 4417 bowheads (421,000 MT). These estimates are approximate, **but the percentages would remain low** even if prey consumption were several **times** higher due to errors in the assumptions or to more intensive utilization **of the** study area in certain years. The percentages **would** be even **lower if** population size is about 7200 with an annual prey requirement of **about** 690,000 MT.

**In** some years, like 1986, a **small** number of bowheads feed **in the study** area for at least several **days--longer** than the population average. **If a subadult bowhead** spent 10 days feeding **for** 16 h/d **in water with** 2 g/m<sup>3</sup> of zooplankton, **it** would consume about 6-8% of its **estimated annual** food requirement. Some whales probably find prey concentrations exceeding 2 g/m<sup>3</sup>, and **it** is possible (although unproven) that a few whales may feed in the study area for more than 10 d in some years. **If so**, those few individuals **could** obtain **an** appreciable fraction of their annual food in the study area.

The relative amounts of feeding in the Canadian vs. Eastern Alaskan **Beaufort** Sea are not known precisely, but Canadian waters clearly are much more important. Most Western Arctic bowheads are in the Canadian **Beaufort** Sea for **at least** 3½-4 mo. **In contrast**, an average bowhead apparently feeds for no more **than** a few days in the Eastern Alaskan **Beaufort** Sea (estimated as roughly 1-2 d **in 1985** and 3-4 d **in 1986**).

Some feeding by bowheads occurs **in late** autumn, **winter** and spring west of our **study** area. Carbon isotope ratios in **zooplankton** and **bowhead** tissues suggest that this feeding may be more extensive than formerly thought, at **least** in **subadult bowheads**. Present uncertainty about the amount of feeding in these seasons is an important limitation in understanding food requirements in the **Beaufort** Sea as a **whole**. **However**, it has **little** effect on conclusions about the importance of the Eastern Alaskan **Beaufort** Sea.

For the population as a **whole**, the **results** indicate that **the null** hypothesis can be accepted:

Food resources consumed in the Eastern Alaskan **Beaufort** Sea **do not** contribute significantly to the annual energy needs of the Western Arctic bowhead stock.

An analogous conclusion can **be** drawn for most individual bowheads **in** most years. However, in some years a few animals that feed **in the** study area for **longer** than others may acquire a significant fraction of their **annual** energy needs in the study area.

**It is** unlikely that accidental **oil spills** would have a significant or **lasting effect** on **zooplankton** in the study area, or **on the** availability of **zooplankton** to **bowheads**. **If any** effects of these types did occur, they **would** be most likely to **occur** in a nearshore feeding area.

Disturbance caused by occasional **vessel** traffic or seismic exploration may displace bowheads temporarily, **but** is unlikely to exclude **them** from important feeding areas. Continuous or repeated disturbance **in** a feeding area

would be more likely to displace whales. Feeding sites in offshore waters are **likely** quite transient, so ongoing disturbance **at** a **single** offshore site is **unlikely** to have a major effect on feeding. Nearshore feeding sites are **more** consistent, and ongoing disturbance in nearshore waters **is** more **likely** to prevent use of a feeding location.



## INTRODUCTION AND OBJECTIVES\*

Most individuals of the Western Arctic (= Bering Sea) population of bowhead whales, Balaena mysticetus, spend the period from May or June to September or October in the Beaufort Sea. During this period they are believed to consume most of the food needed for the entire year. Bowheads, like other baleen whales, are believed to consume little food in winter, although this point is not proven in the case of bowheads.

Offshore exploration for oil and gas has been underway in the eastern (Canadian) part of the Beaufort Sea for more than a decade. The main area of offshore drilling is near the center of the summer range of Western Arctic bowheads. In Alaskan waters, there has been much geophysical exploration for potential oil-bearing structures, and some offshore drilling. Possible effects of these industrial activities on bowheads are of much interest.

Background

Most bowheads spend the summer in Canadian parts of the Beaufort Sea (Richardson et al. 1985a, 1987). However, in some years some bowheads are present in the eastern part of the Alaskan Beaufort Sea for "much of the summer. It is possible that some bowheads do not travel east into the Canadian Beaufort in certain years (Ljungblad et al. 1983). Parts of the Alaskan Beaufort Sea may be important as feeding areas for these individuals.

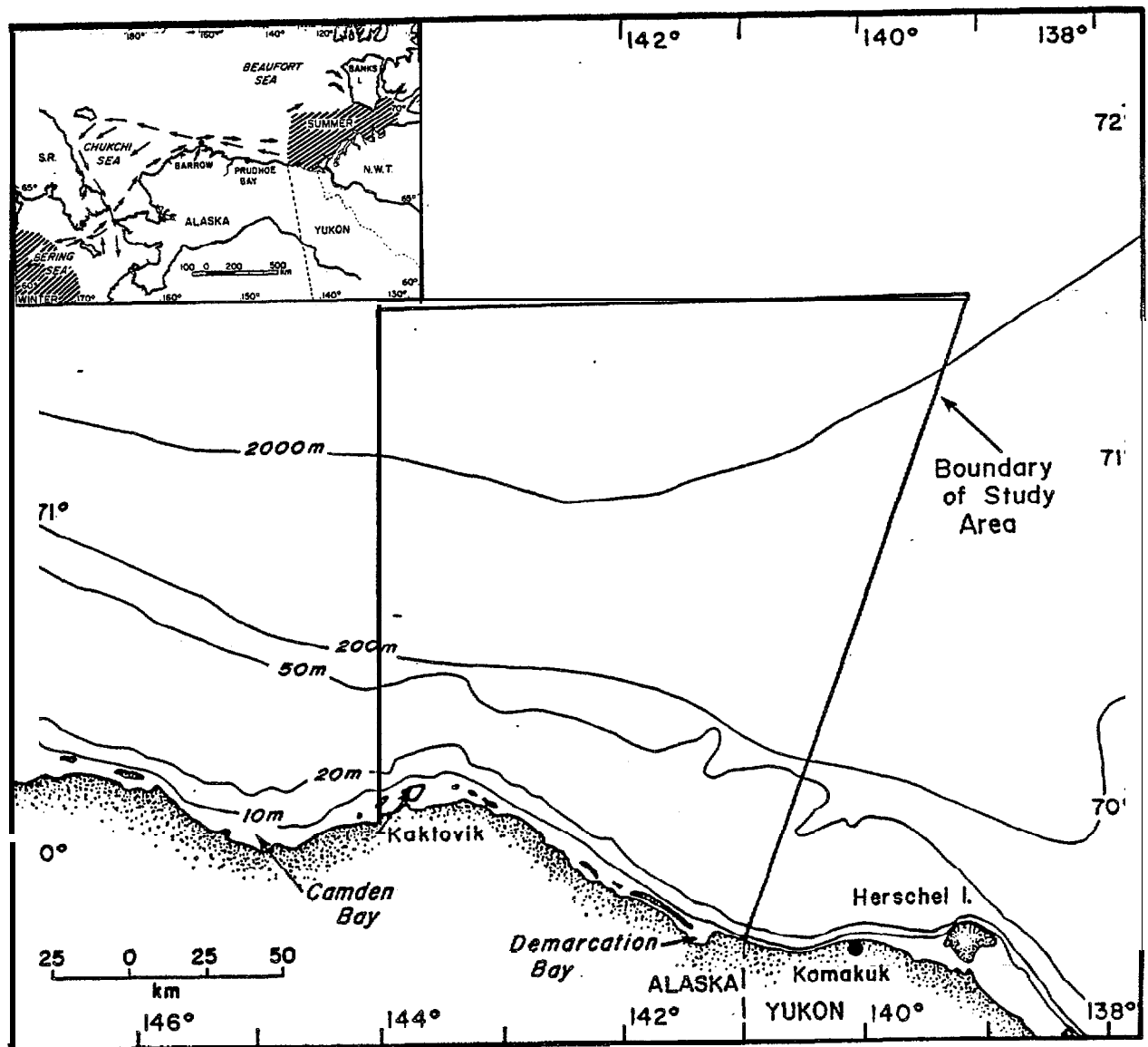
In addition, the western edge of the main summer feeding range is in or near the Eastern Alaskan Beaufort Sea (Fig. 1, inset). In some years, considerable numbers of feeding bowheads occur in that area. This is particularly true in September, when many bowheads have begun a gradual westward movement but are still feeding much of the time. There is zooplankton--mainly copepods and euphausiids--in the stomachs of almost all bowheads harvested in autumn at Kaktovik, a community bordering the Eastern Alaskan Beaufort Sea (Lowry and Frost 1984; Lowry et al. 1987). Some feeding occurs farther west, but feeding frequency seems to decrease as bowheads move west through the Alaskan Beaufort Sea during autumn (Ljungblad et al. 1986a).

Feeding in late summer and autumn may be especially important to bowheads. This, may be the last major feeding period for several months if bowheads, like other baleen whales, do little feeding in winter. Also, the biomass and energy content of arctic zooplankton are higher in late summer and autumn than at other times of year (Lee 1974; Percy and Fife 1981).

Government agencies that regulate offshore exploration for and development of oil and gas are required to assess whether those activities are likely to harm endangered marine mammals such as the bowhead whale. The U.S. National Marine Fisheries Service and the U.S. Minerals Management Service (MMS) have concluded that additional information is desirable to allow a detailed assessment of the possible effects of offshore industrial activities on bowheads that feed in the Alaskan Beaufort Sea.

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\* By W. John Richardson, LGL Ltd.



**FIGURE 1.** Study area for the LGL/MMS bowhead feeding project. Inset: Generalized pattern of seasonal movement of the Western Arctic population of bowhead whales.

Consequently, **MMS** planned a two-year field study of the importance of the Eastern Alaskan Beaufort Sea (Fig. 1) to feeding bowhead whales. That area was chosen because feeding seems **to** be more frequent and prolonged there **than** farther west. A contract for the study was awarded to **LGL Ecological Research Associates Inc.** in mid-July of 1985. **Field** work was conducted **in** September and **early** October of 1985 and 1986.

### Objectives of Overall Project

**The** general purpose of the two-year project was to quantify what proportion of the energy requirement of the Western **Arctic bowhead whale** stock **is** provided **by** food obtained from the Eastern Alaskan **Beaufort Sea**. To do this, **the** main factors considered were

- numbers, activities and residence **times** of bowhead whales in the area;
- prey identity, availability, distribution, patchiness, and energy **content**, along with the oceanographic factors controlling these attributes of the prey;  
amount of prey (and of energy) consumed by the various categories of **bowheads that** fed **in** the study area (**immatures**, adult **males** and females, **etc.**); and
- **total** energy needs of individual bowheads and of the population.

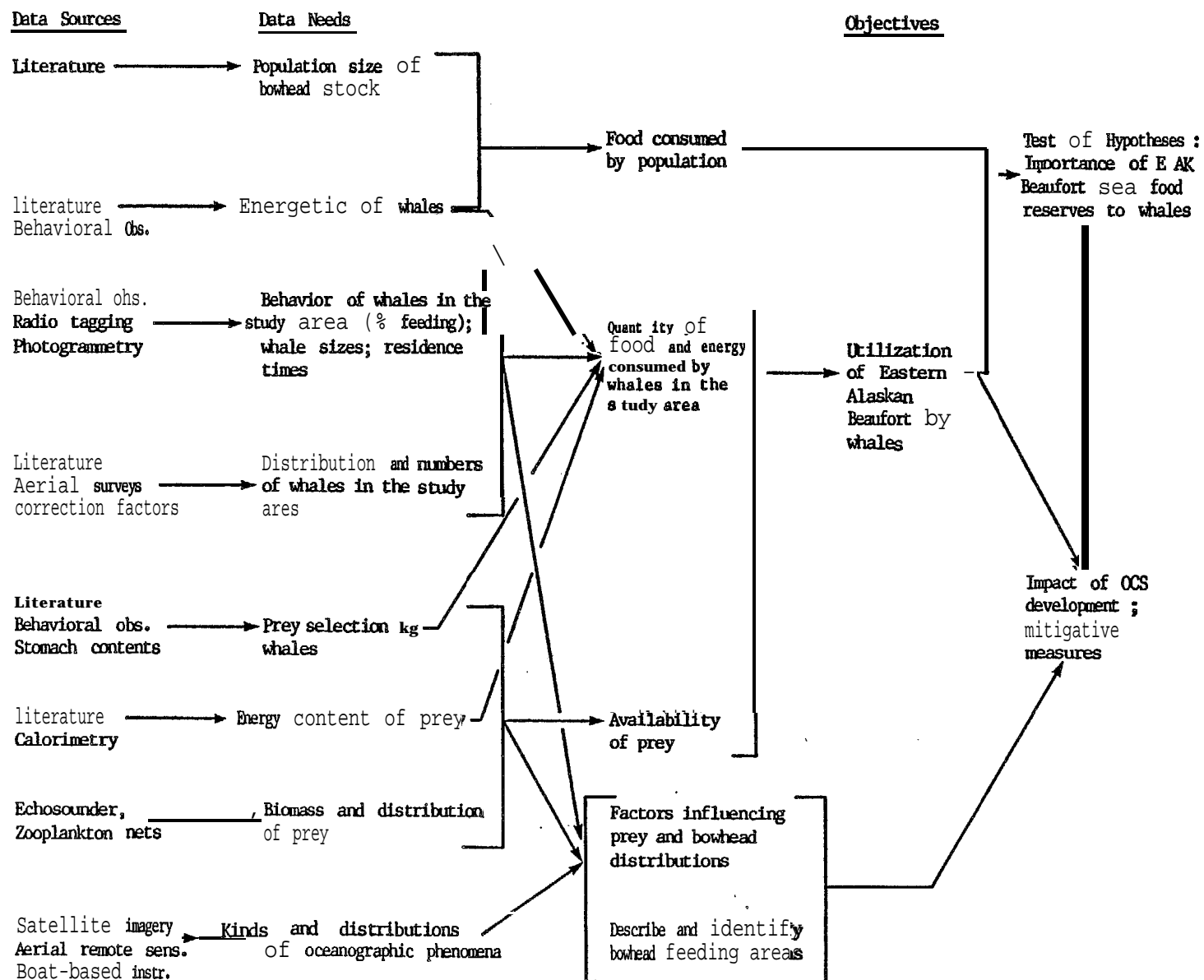
**MMS** itemized the specific objectives of the study as **follows**:

1. Determine the concentration and **distribution** of the **planktonic** food of **bowhead whales** in the Eastern Alaskan Beaufort Sea and correlate with known oceanographic features.
2. Estimate the number of bowhead whales utilizing the Eastern Alaskan **Beaufort** Sea as a feeding area during the summer and **fall**; observe and document their feeding activities, behavior and residence **times**.
3. Estimate **the** degree of utilization of available food resources **in** the Eastern Alaskan Beaufort Sea by the Western Arctic bowhead **whale** stock.
4. Test **the** following **null** hypothesis:

Food resources consumed in the Eastern Alaskan **Beaufort** Sea do **not** contribute significantly to the **annual** energy requirements of the Western **Arctic** bowhead **whale** stock.

Table 1 summarizes the various objectives, data needs, and **possible** data sources. Virtually **all** study components **listed** in Table 1 were **included in the** research. Data available in the literature and from unpublished sources were **also** used where possible and necessary (**LGL** and Arctic Sciences 1985). Results from previous studies and from related concurrent studies (**e.g.** Bradstreet and Fissel 1986; Ljungblad et al. 1986c; Bradstreet et al. 1987) were **important in** addressing questions that required a broader temporal or spatial perspective than **could be attained** from two seasons of fieldwork within our relatively **small** study area.

Table 1. Interrelationships of objectives, data needs and potential data sources.



Objective 1 required to determine the availability of zooplankton within the study area during late summer and early autumn. The primary requirements were to document the biomass of zooplankton present at different locations and depths, and to determine how zooplankton availability was related to water mass characteristics. Previous studies in and near the study area had provided data on the species and numbers of zooplankters present, but not on their biomass, caloric content, or patchiness. Data on average zooplankton biomass were needed to calculate the total amount of food present in the study area. Data on the zooplankton biomass within patches of concentrated plankton were needed to estimate the amount of food that a bowhead might consume by filtering a given amount of water within areas of peak zooplankton abundance. Bowheads were expected to concentrate their feeding within such areas. Data on the caloric content of the zooplankton were needed to translate biomass figures into estimates of energy content.

Objective 2 required us to determine the numbers and activities of bowheads within the study area. Previous aerial survey projects had documented the seasonal occurrence of bowheads in the study area, and the relative numbers of whales present at different locations and times. However, there had been no previous attempts to determine absolute numbers present in the area. To determine absolute numbers, correction factors were developed to account for the many whales below the surface, or missed for other reasons, during aerial surveys. To develop these correction factors, data on the surfacing/diving cycles of whales within the study area were collected. To meet the overall objectives, we also needed to determine how long certain specific whales fed within the study area, i.e. their residence times. Furthermore, we needed to estimate how much feeding was done by an average whale within the study area, and where in the water column the whales fed.

Objective 3 involved estimating bowhead utilization of available food resources within the study area. This was approached using the results from the zooplankton and whale studies conducted to meet objectives 1 and 2. The amount of water that bowheads filter within the study area can be estimated (roughly) based on the observed numbers of whales and their feeding behavior. The results of the zooplankton studies were used to estimate the biomass and energy content of the zooplankton that bowheads consumed. These results were then compared with the estimated amount of zooplankton present.

The overall null hypothesis tested during the project was that food consumed by bowheads in the Eastern Alaskan Beaufort Sea does not contribute significantly to the annual energy needs of the Western Arctic bowhead stock. The results acquired under objective 3 provided the estimate of food consumed within the study area. The annual energy needs of the population were estimated by theoretical and indirect methods. No direct measurements of the energy requirements of bowheads (or other baleen whales) have been made, and there is no practical way to obtain such measurements at present. However, indirect and theoretical estimates of annual energy needs of bowheads can be made by several methods. The 'Energetics of Bowheads' section of this report describes our application of those methods to bowheads. The results are compared with one another and with similar analyses for other species of baleen whales to evaluate their likely reliability. Based on the estimates of (a) food acquired within the study area, and (b) the annual energy needs of the population, we evaluate the correctness of the null hypothesis.

### Approach

To meet these objectives, the 1985 and 1986 field programs included **two** main tasks: **(1)** studies of zooplankton and the physical and biological processes that affect **zooplankton**; and **(2)** studies of the use of the Eastern Alaskan **Beaufort** Sea by bowheads. Each task included several subtasks.

Studies of **zooplankton** and **their** supporting processes included **the** following components:

- **hydroacoustic** surveys to determine **zooplankton** distribution and relative biomass in various areas and positions in the water column;
- net sampling at selected stations and depths to determine **actual** numbers, biomass and species **composition**, and **to** provide **zooplankton** samples for size-frequency, calorimetry, and other analyses;
- boat-based measurements of water temperature, salinity, and chlorophyll;
- **aerial** remote sensing of water **temperature**, chlorophyll and sediment content **on** a near-synoptic basis; and
- digital processing of satellite imagery to acquire synoptic data on **sea** surface temperature and water color on cloud-free days.

**Each of** these types of work was conducted on a broad-scale basis during both years of **study**, and on a fine-scale basis around feeding bowheads in 1986. (Feeding bowheads were very scarce within the official study area in 1985.)

Studies of bowhead whales also included several components:

- **aerial** and boat surveys of **distribution**, numbers, and **movements**;
- observations of feeding behavior and other activities;
- photogrammetric studies of population composition and residence times **of** identifiable individuals in feeding areas;
- **radio** tagging of whales to **study** residence **times**, movements and **other** aspects **of** behavior.

The **first** three of **these** techniques were applied successfully in both years; **radio** tagging **was** successful in 1986.

### Study Area

The official study area was the eastern part of the Alaskan **Beaufort** Sea, from longitude **144°W** east to the approximate eastern edge of the zone whose jurisdiction is in dispute between the U.S.A. and Canada (Fig. 1). The study area extended from the cease of northeastern **Alaska** north to latitude **71°30'N**. More specifically, the eastern edge of the official study area was defined as a straight **line** from (a) the intersection of **141°00'W** and the coast to (b) **71°30'N, 139°05'W**. This area encompasses about 25,470 **km<sup>2</sup>**. Of this, 33% is over the continental shelf, 0-200 m deep; 30% is over the continental slope, 200-2000 m deep; and 37% is far offshore, >2000 m deep. During **late** summer and **early** autumn of previous years, bowhead whales have been seen in all three of these depth strata.

We planned to conduct most of our work in the southern 2/3 of the study area, i.e. in the continental shelf and slope zones (depths 0-200 m and 200-2000 m), with emphasis on the former. There were several reasons:

1. Previous sightings of feeding bowheads within the study area have all been in the shelf zone (LGL and Arctic Sciences 1985; Ljungblad et al. 1986a).
2. Ice cover and other logistical problems for boat operations were expected to increase with increasing distance from shore.
3. Offshore oil exploration in the study area will begin in shallow waters on the continental shelf.

The Naval Ocean Systems Center (NOSC), which also studied bowheads for MMS in 1985-86, conducted occasional aerial surveys north of the 2000 m contour, and provided the data for our use. If NOSC had detected bowheads far offshore, we were prepared to initiate aerial work there. In actuality, NOSC did not detect bowheads far offshore, and we did not work north of the 2000 m contour in either year.

In both years, we conducted some work just to the east of the official study area, between it and Herschel Island (Fig. 1). In 1985, few whales were found in any part of the official study area until late September. However, bowheads were present and feeding along the Yukon coast 20-40 km east, of the official study area during much of September 1985. Consequently our aerial work was extended east to that area. During late September 1985, some bowheads did feed within the official study area, and they were studied during the latter part of the 1985 field season. In 1986, bowheads fed more commonly within the official study area, as well as just to the east. Most of our 1986 work was within the official study area, but we conducted some aerial and boat-based work east as far as Herschel Island.

### Field Season

Choice of the field period for this project involved a number of unpredictable factors and trade-offs. The duration of each year's field program had to be limited to about 25 d of boat-based work and 27 d of aircraft work for budgetary reasons. It was recognized that, during some years, bowhead whales occur in the study area from early August to mid October. However, even in years when some whales are present in August, peak utilization does not occur until mid September (Ljungblad et al. 1986b,c). A further factor that affected scheduling was the expected occurrence of pack and new ice. Pack ice could limit or prevent boat-based work at any time during summer or autumn. Despite the fact that bowheads usually do not enter the study area in large numbers until mid September, it was considered ill-advised to commence a 25-d boat program later than 1 September, given that freeze-up often begins in late September.

Consequently, the field seasons for this project were scheduled to be about 1-25 September for boat work and about 1-27 September for aircraft work. In fact, the 1985 boat work ended on 20 September after pack ice moved into most of the study area and new ice began to form rapidly. Because bowheads

were present in the study area in late September 1985 and because the early termination of boat work had eased funding constraints, the 1985 aircraft work was extended until 3 October. In 1986, weather and ice conditions were unusually favorable. The aircraft and the primary boat both operated throughout their scheduled field periods during September 1986.

Additional **data** on zooplankton in the Alaskan Beaufort Sea were obtained during the 'Polar Star' icebreaker cruise in October 1986. The primary purpose **of** this cruise was to conduct a **NOAA** physical oceanography study. However, personnel from the present project were able to obtain **zooplankton** samples **from** the 'Polar Star' on 4-17 October.

Additional data on utilization of the study area by bowhead whales in 1985-86 came from other aircraft conducting 'whale surveys. **NOSC** conducted surveys in the Alaskan Beaufort Sea, including our study area, from **early** August to mid October 1985 (**Ljungblad et al. 1986c**), and from mid August to early October 1986 (**NOSC** in prep.). Other LGL projects also provided survey coverage in or near our study area from late August to mid October 1985 (**Davis et al. 1986b**; Evans and Holdsworth **1986**; **McLaren et al. 1986**), and **early** September to early October 1986 (Evans et al. in prep.). Results from these other projects are taken into account here.

#### Boat Logistics

The 'Annika Marie', a 13-m research vessel based at **Prudhoe** Bay, was chartered **in** both 1985 and 1986. This boat conducted broad-scale surveys of **zooplankton** within, the shelf zone, using **hydroacoustic (echosounding)** techniques as well as conventional net sampling. When concentrations of feeding whales occurred within the study area, the boat was **also** used to determine the fine-scale distribution of plankton near the feeding whales. Water temperature, salinity, and chlorophyll were measured during both **broad-** and fine-scale sampling. During 1985, the same boat was used as a base for attempts to radio tag whales within feeding concentrations; during **1986** a separate smaller boat was available for the radio tagging.

In 1985, broad-scale sampling was conducted from 4 to **18** September along three onshore-offshore transects between Kaktovik and Demarcation Bay. Work was interrupted by bad weather on 9 and 15-17 September, and by engine **failure** on 11-13 September. Very few bowhead whales were in the study area during this ice free period. Hence, almost all of the 1985 boat time was devoted to broad scale zooplankton and **hydroacoustic** surveys, along with associated physical measurements. In the absence of concentrations of feeding whales, it was **not** possible to conduct fine-scale zooplankton sampling around feeding bowheads, or to radio tag **bowheads**. A storm on 15-17 September 1985 brought heavy ice into **most** of the study area. Thereafter, new ice began to form in the narrow nearshore lead through which the vessel had to return west to **Prudhoe** Bay. On 19-20 September, the vessel returned to **Prudhoe** Bay; ice conditions in the study area deteriorated further after 20 September.

In 1986, whales were already feeding in and just east of the official study area when the boat arrived on 3 September. From 4 to 7 **September**, we conducted fine-scale sampling around feeding whales. From then until the **end** of the charter period, the boat crew sampled along all four of the planned



broad-scale transects extending from nearshore waters **out to the** 200 m **contour**. Weather conditions were remarkably favorable until 20 September **in 1986**, there was very **little** ice, and there were no mechanical problems.

**In 1986**, a second smaller boat, an 8-m Munson, was made available by NOAA and MMS for **use by** our radio tagging crew. It was **to be used from 1 to 25** September. Although **this** vessel was delayed in reaching the **study** area, it was used **there** on 9-25 September 1986, and five **bowheads** were radio tagged.

As noted above, additional **zooplankton** sampling was conducted from the U.S. Coast Guard icebreaker 'Polar Star' on **4-17** October 1986. This work was designed to obtain **zooplankton** samples (a) from far-offshore parts of the official study area that **could not** be reached with the 'Annika Marie', and (b) from areas west **of** the official study area.

#### Aircraft Logistics

The aircraft program was designed to **determine** the distribution, numbers and activities of bowheads within the study area. The aircraft crew **also obtained** calibrated vertical photographs of **bowheads**, from which whale sizes and residence times of identifiable animals were determined. During **transect** surveys **within** the first half of each **field** period, the aircraft carried **aerial** remote sensing equipment that measured **water** temperature and **color**. The aircraft crew **also** monitored for radio tagged whales.

A Twin Otter aircraft (DHC-6-300) on full-time charter for the project was based at Kaktovik from **4 September to 3 October, 1985** and from **2 to 28 September 1986**. The aircraft was equipped with **bubble** windows to facilitate observations, a GNS 500A Very Low Frequency navigation system, a ventral camera port for vertical photography of whales, and antennae and receivers for monitoring **sonobuoys** and radio **tags**. One or more flights were made **on** every day when weather allowed. We made **totals** of 26 and **36** offshore flights **in 1985** and **1986**, respectively, **plus** several additional flights to calibrate equipment and, in **1986**, to transport **fuel** for the radio telemetry **boat**. Total offshore flight hours were 99.4 h in **1985** and **129.9** h in **1986**. We were grounded by bad weather, i.e. some combination of **fog, low ceiling**, and high sea **state**, on **12** of **29** days in **1985**, but on **only 3** of **25** days in **1986**. The **latter** is a remarkably low ratio for this area and season.

#### Report Organization

This report is an integrated and self contained account of the results from the 1985 and 1986 **field** programs, **along with** a review of earlier **literature** and data. Some additional details concerning pre-1985 and **1985** data appear in an earlier literature review (LGL and Arctic Sciences 1985) and in our **report** on the **1985 field** program (Richardson [cd.] 1986). However, **all** **results** important to the objectives of this **study** are presented here.

The first major section of this report describes the **water** mass characteristics in and near the study area during the **1985** and **1986 study** periods. It **also** includes the most relevant pre-1985 historical **data**. These physical data are important in understanding the distribution of the **zooplankton** prey of **bowheads**. The 'Water Masses' section is **based on**

traditional boat-based measurements plus airborne and satellite remote sensing techniques. This section was written by subcontractors **D.B. Fissel**, **J.R. Marko** and **J.R. Birch** of Arctic Sciences Ltd., and **G.A. Borstad**, **D.N. Truax** and **R. Kerr** of **G.A. Borstad Associates Ltd.**

The second section documents the **zooplankton** during the 1985-86 study periods. Both net samples and quantitative hydroacoustic data are considered. This section provides the first systematic data on the biomass, patchiness and caloric content of zooplankton within the study area. The zooplankton near feeding whales is compared with that elsewhere in the study area. Comparisons are made with the results of a closely related study conducted in the Canadian **Beaufort** Sea in 1985-86 (**Bradstreet** and **Fissel** 1986; Bradstreet et al. 1987). **Zooplankton** data collected over a broader area of the Alaskan Beaufort Sea in October 1986 are **also** described for comparative purposes. This section was written by **W.B. Griffiths** and **D.H. Thomson** of LGL, and **G.E. Johnson** of subcontractor **BioSonics** Inc.

The third section describes the seasonal distribution of bowheads in and near the study area in the 1985-86 study periods, the number of whales present, the behavioral activities of these whales, and the sizes, residence times and movements of some individuals. Selected historical data from surveys during 1979-84 are **also** summarized to place the 1985-86 data into a broader perspective. This section was written by **W.J. Richardson** and **G.W. Miller** of LGL, and **B. Würsig** of Moss Landing Marine Labs.

The fourth section describes an attempt to determine the "amount" of bowhead feeding in the Beaufort Sea vs. elsewhere in the bowhead's range. This work, by **D.M. Schell**, **S.M. Saupe** and **N. Haubenstock** of the University of Alaska, is based on analyses of the isotopic composition of the tissues of bowheads and their zooplankton prey. The isotopic composition of **zooplankton** appears to vary geographically, and this variation may serve as a tracer of regional feeding dependencies. An important by-product of this work was the development of a method for determining the approximate ages of many bowheads based on the isotopic content of **their** baleen,

The fifth section, by **D.H. Thomson** of **LGL**, outlines our current understanding of the **annual energy needs** of bowheads, and the extent to which these requirements were met within our study area in 1985-86.

The sixth section, by **D.H. Thomson** and **W.J. Richardson** of LGL, is entitled 'Integration'. It draws together the various types of data acquired in the study. A '**Conclusions**' section completes the main text.

Bibliographic details for references cited in **all** sections are given in a **single** 'Literature Cited' section. Appendices 1-3 of this report, **along** with Appendix 3 of Richardson (**ed.**, 1986), contain the raw data from the 1985-86 **zooplankton** sampling. Detailed results of the radio telemetry work appear in Appendix 4.

## WATER MASS DISTRIBUTIONS\*

### Introduction and Objectives

As part of **the study of** the importance of **the** Eastern Alaskan Beaufort Sea to feeding **bowhead** whales, sponsored **by** the U.S. Minerals Management Service, **the** relevant physical oceanographic features **of** the area **were** investigated. Initially, previous oceanographic and available satellite data were reviewed and analyzed (**Fissel et al. 1985**). In September of 1985 and 1986, a field program was conducted to map and analyze **the** spatial distributions of physical oceanographic properties. The physical oceanographic observations were obtained concurrently **with** the biological components of the **study**, described later **in** this report.

Information about physical oceanographic conditions was needed because **zooplankton**, the primary food source for **bowhead** whales, are affected **by** physical as **well** as biological processes. Based on previous **studies** elsewhere, **zooplankton** abundance in the study area was expected 'co be **highly** variable, both horizontally and vertically, and **bowhead** whales were expected **to** concentrate their feeding in **the** denser patches of **zooplankton**. Consequently, **it** was necessary to determine the factors that affect the local abundance **of** **zooplankton**. Mechanisms **that** concentrate **zooplankton**, and their relationships to physical processes, are not **well** understood. However, physical processes are known to affect **zooplankton** in **two** general ways:

1. Through enhancement of primary productivity, which increases **the** food **supply** for **zooplankton**. This **could occur**, for example, **by** means of **upwelling** of nutrient-rich water into the active surface **layer** from depth;
2. Through generation of convergence mechanisms (fronts **and** eddies), which serve **to** concentrate **zooplankton** directly.

### Physical Mechanisms for Zooplankton Concentration

Primary production can be enhanced by **upwelling** processes, which replenish the nutrients in the mixed **layer** of the ocean. If the **upwelling** and enhanced primary production are sufficiently **prolonged**, growth of **zooplankton** stocks can **also** be enhanced as a **result of** the **upwelling**. **Upwelling** due to wind-driven transport away from coastlines has been observed over the Alaskan **shelf** (Hufford 1974; Aagaard 1981). **Upwelling** at fast- and pack-ice edges (Buckley et al. 1979; Niebauer 1982; Johannessen et al. 1983) could **also** be important in the Eastern Alaskan Beaufort Sea.

Given the relatively long lifetime of most **zooplankters**, **zooplankton** concentrations often develop when existing **zooplankton** become concentrated **rather** than through enhanced **zooplankton** growth. Several physical processes **are capable** of concentrating **zooplankton**. Oceanic fronts between adjoining

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\* By David B. Fissel, John R. Marko and J. Rick Birch of Arctic Sciences Ltd. and Gary A. Borstad, Dawson N. Truax and Randy Kerr of G.A. Borstad Associates Ltd.

water masses of dissimilar properties are often associated with convergent **flow** patterns. Fronts and eddies occur over spatial scales as small as tens of meters, **usually** associated with areas where differing water masses abut. Such fronts are recognizable **at** the surface by lines of flotsam or change in sea state, and are often the sites of intense biological activity (Bowman and **Esaias 1978**; Parsons et al. 1977). Factors conducive to the formation of oceanic fronts include the presence of water masses of differing characteristics, complicated coastal morphology (lagoons, barrier islands, points), steeply sloping bottom topography along the shelf break, and periodic coastal **upwelling**. All of these factors are known or suspected to occur in the study area. Tidal fronts and associated tide-forced internal waves may **also** generate surface **slicks** and concentrate **zooplankton** (Shanks 1983). This phenomenon requires a **shelf, pycnocline** and tides; **all** are present in the **Beaufort** Sea. Tides and tidal currents **are**, in fact, weak in most parts of the Beaufort Sea and zooplankton concentration is more likely to be affected through the internal waves generated by other non-tidal currents. Another process of potential importance in producing convergence zones is wind-induced Langmuir circulation **cells**, occurring as vertically-oriented vortices within the surface **layer**.

In the southeastern Beaufort Sea, the wind is the principal force affecting the hydrographic regime. It governs the location of the Mackenzie River plume and its associated front, current directions, and the location and intensity of localized **upwelling** (Thomson et al. 1986). It is suspected that wind, through its effects on the advection of differing water masses in the **southeastern Beaufort** Sea, may affect patterns of zooplankton abundance and, indirectly, the distribution of **bowhead** whales in the Canadian Beaufort Sea.

These effects may extend west into the Alaskan Beaufort Sea. Wind direction and speed appear to have a large effect on circulation patterns in the nearshore and inner shelf portion of the Alaskan Beaufort Sea (Aagaard 1978). Wind could affect the locations of fronts, eddies and **upwellings**, and thus **alter zooplankton** distribution in the study area.

#### Literature Review and Analysis of Previous Data

Prior to the 1985 and 1986' **field** studies, physical processes that **could** influence the abundance of **zooplankton** in the study area during the late summer-early autumn period were examined through a literature review and **analyses** of available oceanographic data (**Fissel et al. 1985**). Some of these pre-1985 data are summarized in the 'Physical Setting' and 'Results' sections of this report. The data utilized in that review consisted of (a) existing oceanographic data collected during ship-based cruises to the study **area** from 1950-1978, and (b) **digital** satellite imagery from **late** summer over the years 1980-1984,

The literature review demonstrated that large-scale **upwelling** occurs frequently within the study area. This was demonstrated by (a) upward tilting of salinity contours along nearshore-offshore oceanographic transects, and (b) the presence of cold surface waters along the eastern Alaskan and Yukon coastlines as detected from **satellite** imagery. Both observations are consistent with the occurrence of classical coastal **upwelling** driven by easterly winds, the dominant wind direction within the region. **Upwelling**

along ice edges may also be important, but no direct evidence was available to document the existence of this process.

During the literature review, we used satellite data to identify large-scale fronts, i.e. sharp gradients in Temperature or turbidity over horizontal scales  $\geq 1$  km. In the Eastern Alaskan Beaufort Sea, large-scale fronts were most common when there was westward advection of warm waters from Mackenzie Bay along the outer edge of the continental shelf and over the continental slope. Fronts were also observed in the nearshore zone, within 5 km of the coastline, due to freshwater discharge from local rivers or lagoons. Fronts may also occur near melting sea-ice, although these fronts were difficult to examine due to lack of suitable shipboard data or satellite imagery (Fissel et al. 1985).

#### Field Measurement Programs: 1985 and 1986

The physical data collected during the 1985 and 1986 field programs were intended to provide further information on the oceanographic processes described above, and to assist in interpreting simultaneous observations of zooplankton and bowhead whales. Using satellite images and airborne remote sensing techniques, the synoptic distributions of surface oceanographic features throughout the study area were mapped. Horizontal and vertical profiles of temperature and salinity were acquired by boat-based sampling along oceanographic transects. Coordinated boat- and aircraft-based sampling provided information on smaller spatial scales than had been available previously. The concurrent measurements of zooplankton abundance and physical oceanographic data were designed to permit testing of the hypotheses that zooplankton aggregations tend to occur in specific water masses, and in or near fronts, eddies and areas of upwelling.

This 'Water Masses' section of the report presents a thorough description of the water mass distributions in the Eastern Alaskan Beaufort Sea for the period when that area is used most intensively by bowhead whales (late summer and early fall). The description is derived from the 1985 and 1986 data, as well as the historical review of Fissel et al. (1985).

#### Physical' Setting

This subsection describes the main physical characteristics of the Eastern Alaskan Beaufort Sea. It is based mainly on our review of pre-1985 data (Fissel et al. 1985), but it includes a summary of ice and wind patterns in 1985-86. This subsection is intended to provide background material helpful in understanding the later presentation of our detailed results from 1985-86.

#### Bathymetry and Oceanographic Regimes

The study area (Fig. 2) includes the easternmost portion of the Alaskan Beaufort Sea, from east of Demarcation Bay ( $141^{\circ}\text{W}$ ) to west of Kaktovik ( $144^{\circ}\text{W}$ ). It extends from the coast north to  $71^{\circ}30'\text{N}$ , an area approaching abyssal depths. The bathymetry is important in characterizing the water properties and circulation of this region (Aagaard 1978).

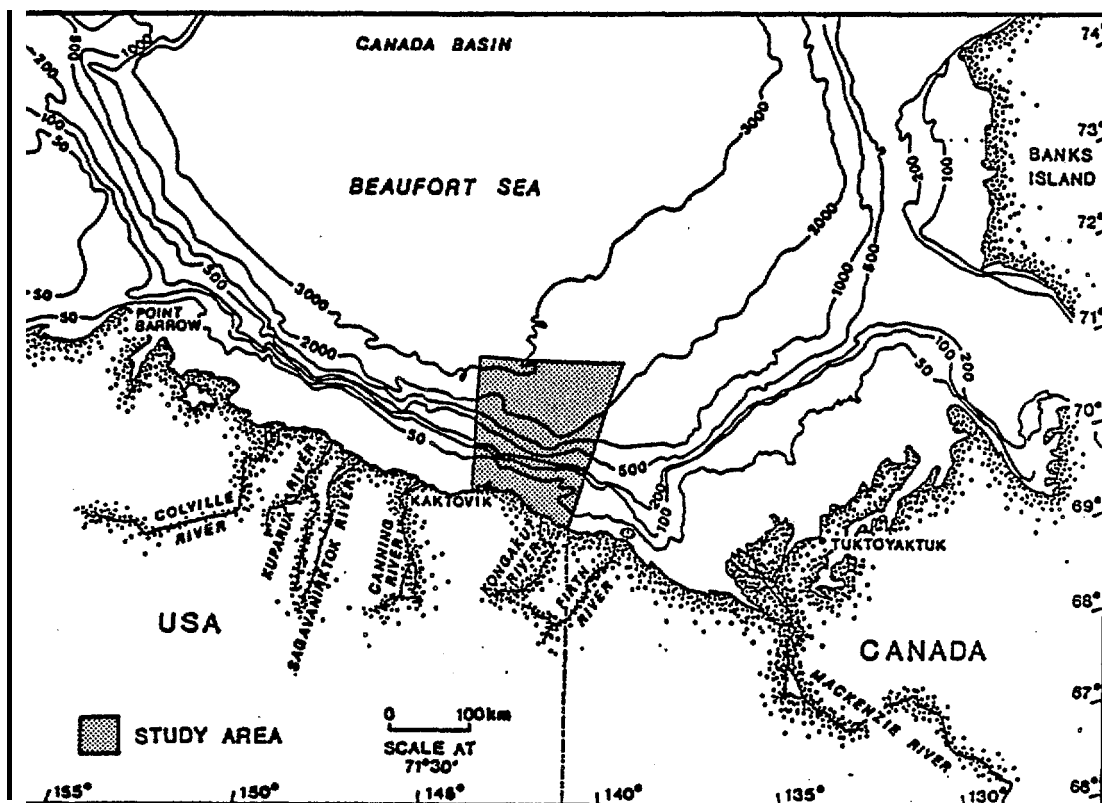


FIGURE 2. A map of the Beaufort Sea, showing the study area, major bathymetric features and important rivers.

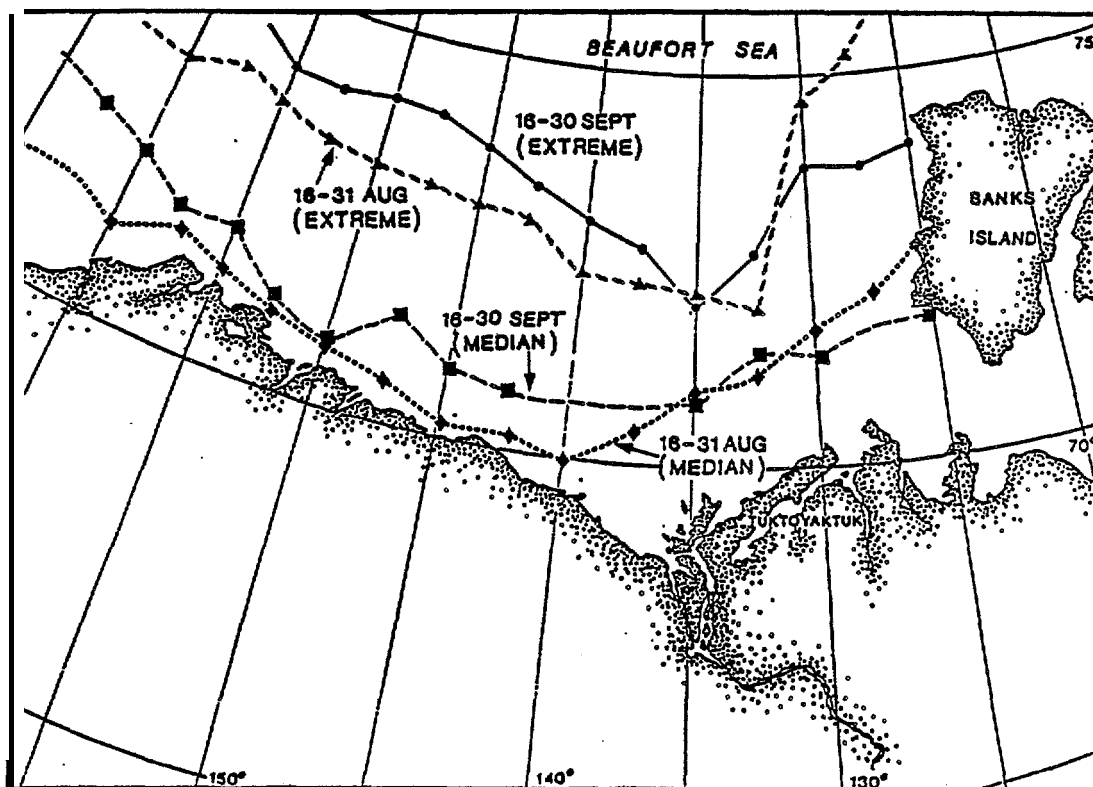


FIGURE 3. Extreme and median positions of the pack-ice edge in late summer (after Brewer et al. 1977).

The nearshore zone (depths **0-10 m**) **consists** of extensive shallows, partially contained by chains of barrier islands **but** interspersed with more exposed shallow water **embayments**. This nearshore zone is 4 to 12 **km** wide.

The continental shelf zone extends seaward from the **10 m isobath** to the **shelf** break, where the offshore **slope** increases abruptly. The shelf zone **ranges** in width from 25 to 55 **km**. In the study area, the outer boundary of the continental **shelf** roughly coincides with the **50 m isobath**. From the **shelf** break to the **2000 m isobath** is the continental slope zone, which is characterized by a much **larger** bottom **slope** than occurs in the adjoining zones. The continental **slope** zone has a width of **60 km** in the **study area**. Prominent canyon-like indentations **likely** influence the circulation **patterns**. It is in this zone that **important lateral** exchanges occur between the waters of the offshore and shallower regions (Aagaard et al. 1978).

Beyond the **2000 m isobath**, the waters deepen less rapidly. At depths of **3500 m** or more, the bottom becomes comparatively featureless over the **abyssal** depths of the Canada **Basin** of the **Arctic Ocean**.

#### Regional Sea-Ice Patterns

Sea-ice is also a major determinant of oceanographic conditions in this area. Landfast ice occurs **along** the **coast**; it forms in late September or **early** October and deteriorates in June near **major** river estuaries. Breakup and dispersal of the coastal band of **landfast ice** is usually **complete** by **mid-July**. In contrast, the offshore portion of the ice **cover**, the **Arctic pack-ice**, is composed of both multi-year and first-year ice **floes** and sometimes includes ice islands. The pack-ice generally retreats during the summer **months**, its southern edge forming the northern boundary of open water after the break-up of the **landfast** ice (Fig. 3). Year-to-year variations in wind and current patterns cause variations in the location of the pack-ice edge. This, in turn, results in major **annual** differences in the expanses of open-water and in the duration of the open-water season.

1985 Sea-Ice Patterns,--The offshore retreat of the pack ice followed the **normal** pattern in the Eastern Alaskan study **area**, but was unusually **late** in the easternmost portion of the Canadian **Beaufort Sea**. As a result, unusually severe ice conditions were experienced in the Canadian Beaufort Sea, particularly off the **Tuktoyaktuk** Peninsula and near the mouth of **Amundsen** Gulf (longitudes **125°W-134°W**). Ice conditions in that eastern area were worse during July to September 1985 than during any other summer (aside from 1974) from 1971 to 1985. Only in 1974 did ice conditions **limit** the open water area to smaller values.

In contrast to the unusually severe ice conditions farther east, the offshore retreat of the pack-ice edge from the **eastern** Alaskan and Yukon **coastlines** followed the typical climatic **pattern**, beginning in **early August** (see Fig. 2-5 in Fissel et al. 1986, p. 13-16). From mid-August to mid-September, the area of open water exceeded median **values** expected for this time of year. Under the influence of strong west winds from 14-23 September 1985, the pack ice moved shoreward. This greatly reduced the amount of open water off eastern Alaska in late September 1985. Aside from the possible

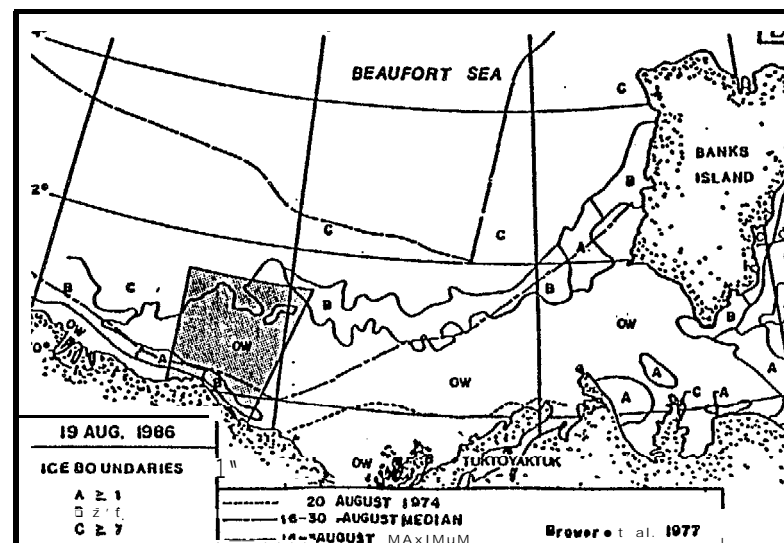
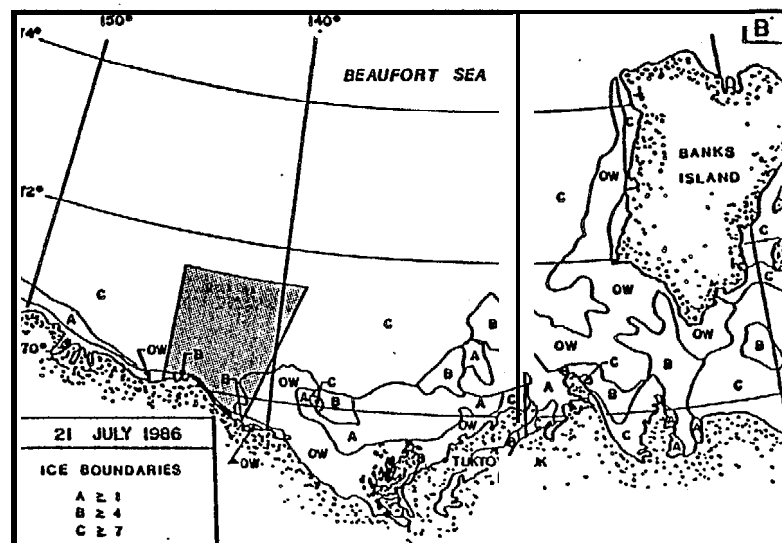
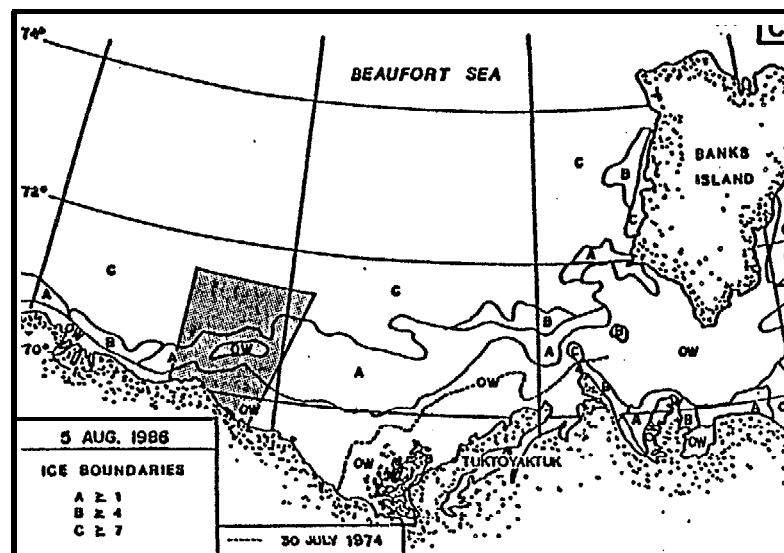
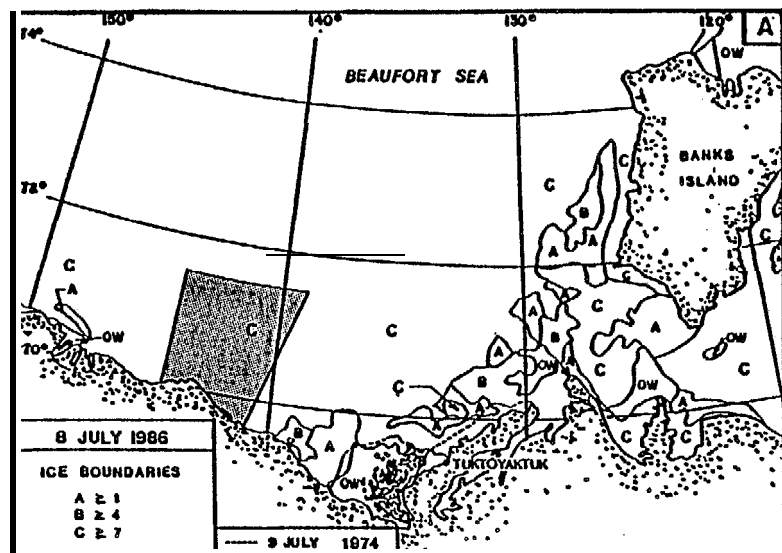


FIGURE 4. Ice concentrations (tenths) in the Beaufort Sea on (A) 8 July 1986, (B) 21 July 1986, (C) 5 August 1986, and (D) 19 August 1986. Ice conditions for 1986, and for the severe ice year of 1974, are derived from charts prepared by the Atmospheric Environment Service, Ottawa. Median and maximal open water (OW) conditions are shown for the same time of year, from Brewer et al. (1977). The shaded area represents the official study



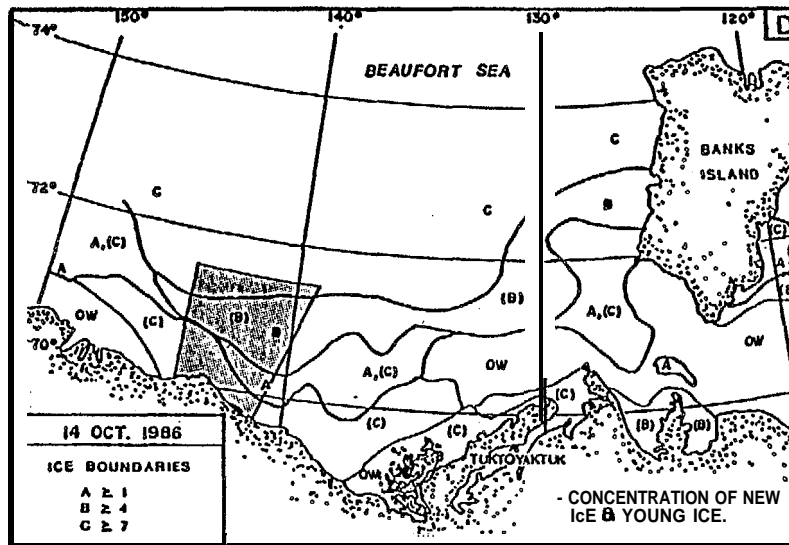
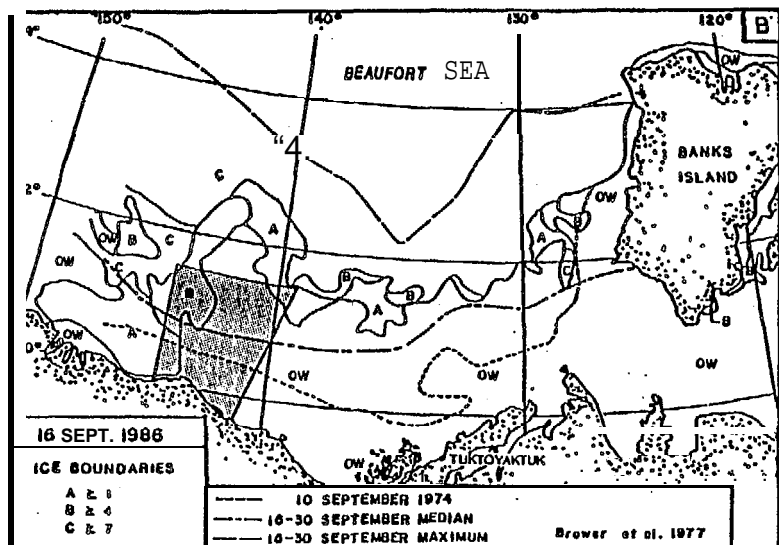
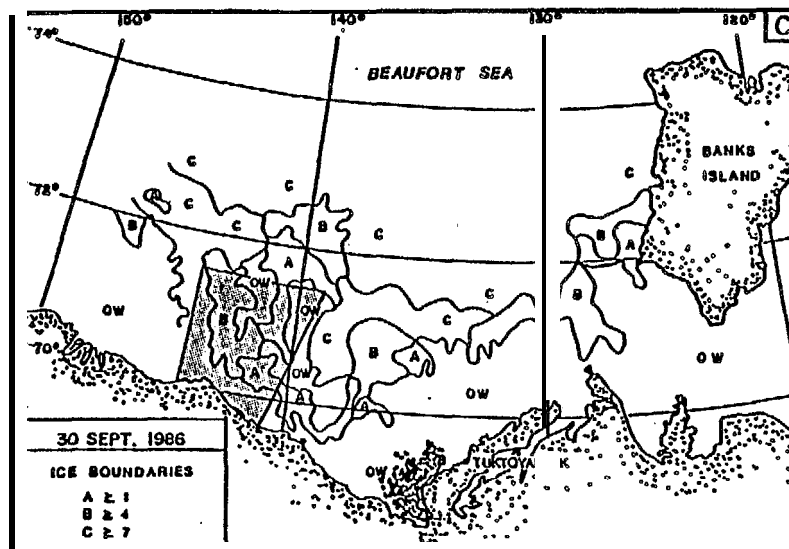
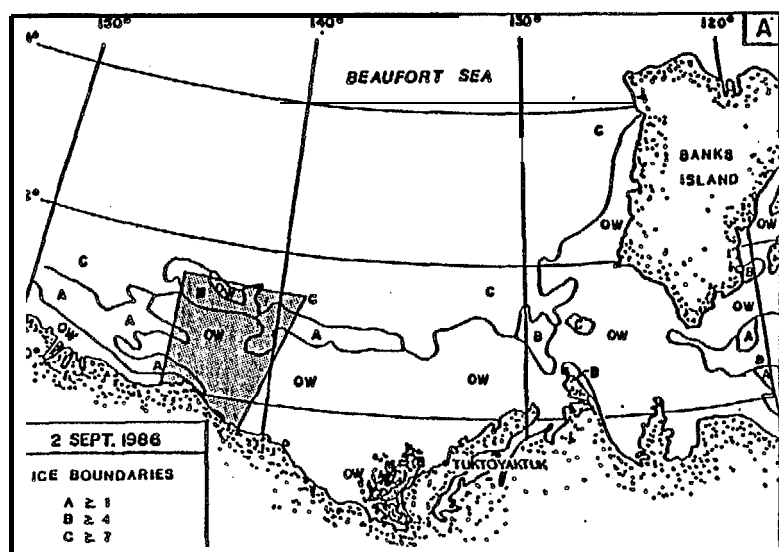


FIGURE 5. Ice concentrations (tenths) in the Beaufort Sea on (A) 2 September 1986, (B) 16 September 1986, (C) 30 September 1986, and (D) 14 October 1986. Presentation as in Fig. 4.

effects of this ice on biological processes, it also curtailed our boat-based and satellite observations of the water characteristics.

**1986 Sea Ice Patterns.**--Off eastern Alaska, sea-ice conditions during the summer of 1986 were again fairly typical of those over the last 15 years. Local clearing of coastal sea-ice was well underway by early July (Fig. 4A) in regions adjoining the Mackenzie River delta and at the entrance to Amundsen Gulf (the so-called Cape Bathurst Polynya; Smith and Rigby 1981). Open water also appeared off the Alaskan coast near the Sagavanirktok, Kuparuk, and Colville River estuaries. Dispersal and melting of sea-ice floes continued throughout August (Fig. 4C, 4D). By mid-August, most of the broad continental shelf of the Canadian Beaufort Sea was clear of sea-ice. The open water area extended west to 146°W, with the exception of a band of scattered floes 10 to 50 km off eastern Alaska.

In September, the location of the pack ice edge remained largely unchanged from August, between 71°N and 72°N (Fig. 5A, 5B). During mid-September, higher concentrations of sea-ice floes moved southeast into the extensive area of open water in the Eastern Alaskan Beaufort Sea. These intruding ice floes generally remained west of 143°W, and to the east open water extended over 200 km from shore. By the end of September (Fig. 5C), scattered ice (2 to 8 tenths) occupied much of the Eastern Alaskan region, with extensive open water west of 145°W and east of Herschel Island. By mid-October (Fig. 5D), much new sea-ice had formed, particularly in the Eastern Alaskan and Mackenzie Bay regions.

### Weather Patterns

**Historical Wind Patterns.**--Wind is the dominant mechanism driving the circulation of the nearshore and inner shelf zones. Continuous wind measurements, spanning a 35-year period, are available within the study area at Barter Island (Kaktovik). These data reveal that coastal winds blow predominantly in two directions: from ENE-E (55-100°T) 35% of the time, and from WSW-W (235-280°T) 23% of the time (Fig. 6). The mean wind speed is approximately equal (6-7 m/s) for both wind directions.

The coastal winds in the Beaufort Sea become progressively less dominated by easterly winds with increasing distance east from Point Barrow. At Point Barrow, the most frequent wind direction is easterly for all seasons. During summer, when west winds are most common, they occur only half as frequently at Barrow as at Barter Island (Fig. 6). In the Canadian Beaufort Sea, by comparison, east and W-NW winds are similar in frequency during summer.

Coastal winds are modified by mesoscale atmospheric effects (Kozo 1979; Kozo and Robe 1986), mountain barrier baroclinicity (orographic effects), and sea breezes. The Brooks Range, which is within 100 km of the coast, enhances local westerly winds (Schwerdtfeger 1974). This effect is most pronounced during winter when the atmosphere is very stable. However, in an unusually prolonged period of west winds in August and September 1983, orographic effects of the Brooks Range extended at least 50 km offshore through the study area (Kozo and Robe 1986).

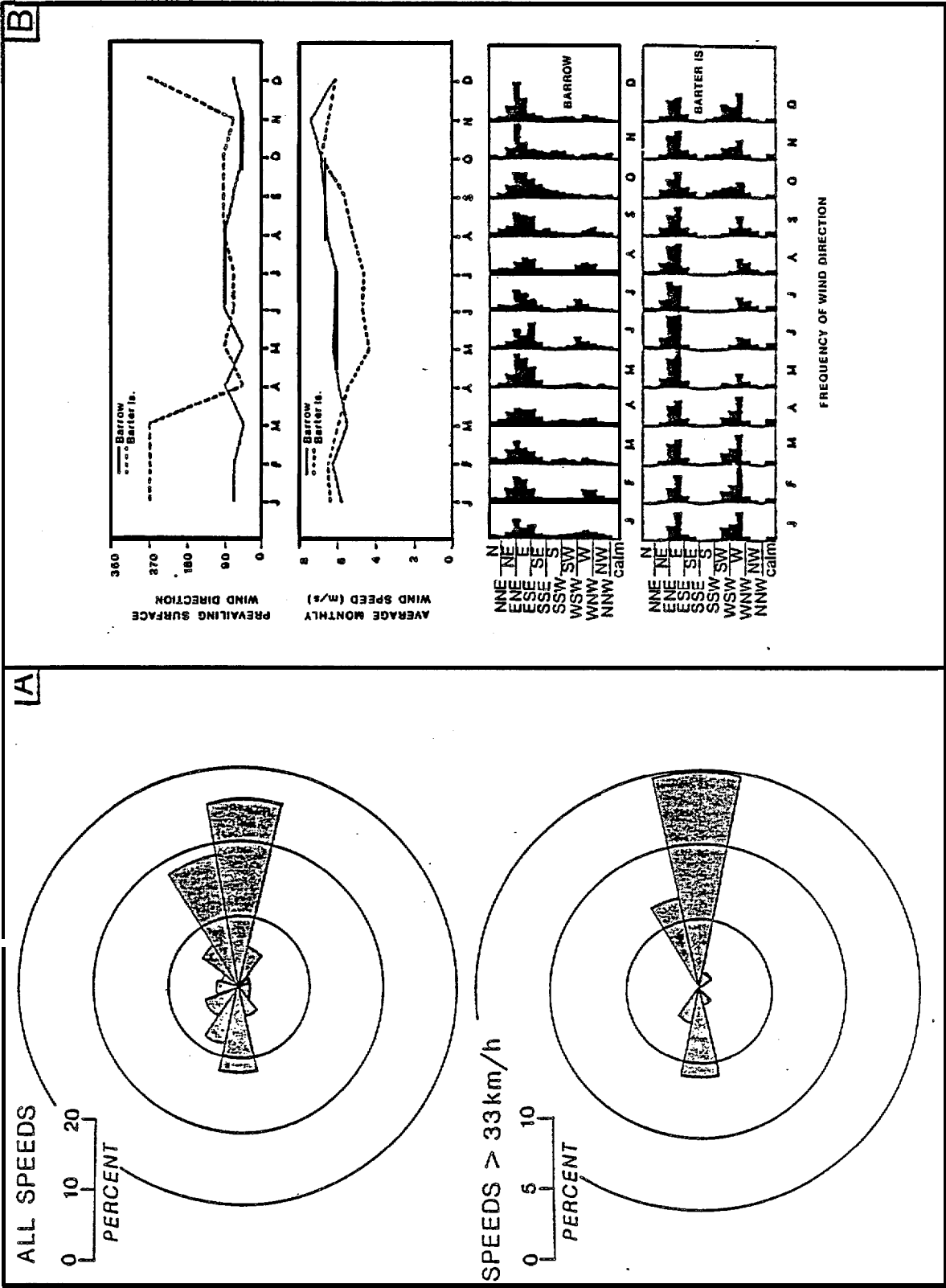


FIGURE 6. (A) Summer wind roses for 1949-1984 observations from Barter Island. (B) A comparison of monthly wind directions between Barter Island and Point Barrow (after Envirósphere 1984).

Sea breezes, driven by differential solar heating of the land and ocean during summer, occur daily over reduced spatial scales. Kozo (1984) estimates that sea breezes can significantly **alter** the synoptic winds up to 20 km offshore. The effects of the sea-breeze forcing are (1) to maintain a westward **alongshore** surface current as much as 20 km offshore, which promotes **lagoon flushing** even during periods of weak opposing (westerly) wind; (2) to produce wind-driven current shears about 20 km offshore where the transition to synoptic wind conditions occurs; and (3) to mask synoptic wind directions within 20 km of the coast (Kozo 1984).

1985 Wind Patterns.--Weather data from Barter **Island** revealed that the prevailing wind was easterly **in** August and September 1985 (Fig. 7), **in** agreement with the climatic normals for the Eastern Alaskan **Beaufort Sea** (Fig. 6).

The easterly winds were occasionally interrupted by periods of west to northwest winds associated with the passage of low pressure weather systems from west to east through the **Beaufort Sea**. Five well-defined westerly wind events occurred in August-September 1985: 8-9 **Aug**, 15-17 **Aug**, 4-6 **Sept**, 14-17 **Sept** and 19-22 **Sept**. Of these, the two events during mid-September were of unusually **large** intensity and duration. For two days (16-17 **Sept**) strong northwest winds blew consistently at 15-20 m/s. Following a 1 d interval of weak winds, moderate west to northwest winds again developed for 3 d (19-22 **Sept**) at 6 to 15 m/s.

1986 Wind Patterns.--In general, winds during the first **half** of September 1986 were weaker and **less** consistently from the east than during the corresponding period of 1985. Winds from 'late August through the first half of September 1986 were generally light and variable, punctuated by the occasional significant wind event (Fig. 8). On August 22-24, strong northwest winds reached speeds of 15 m/s. A shorter period of east winds occurred on 28-29 August, with speeds up to 14 m/s. From 30 August to 16 September, winds **at** Barter **Island** were weak to moderate, never exceeding 10 m/s. The winds blew predominantly from the east, although occasionally WNW and NW winds occurred, most noticeably on 12-13 September. On 16 September 1986 there was a **short** period of relatively intense northwest winds, followed by weak winds over the next few days. Beginning on 20 September, winds intensified greatly; there were strong west winds on 20-21 September (up to 17 m/s) and 23-25 September (up to 15 **m/s**).

### River Discharges

Fresh water entering the study area from rivers can exert an important influence on water properties and circulation patterns in estuaries and adjoining regions. Of the seven largest rivers draining into the Beaufort Sea **along** the mainland coast (Table 2), the Mackenzie River contributes **well** over 80% of the total river discharge. The Mackenzie River has a mean **annual** discharge of  $3.04 \times 10^{10} \text{ m}^3$ , approximately 30 times greater than the **Colville** River, the largest Alaskan river. These rivers are located approximately 200-300 km on either side of the study area.

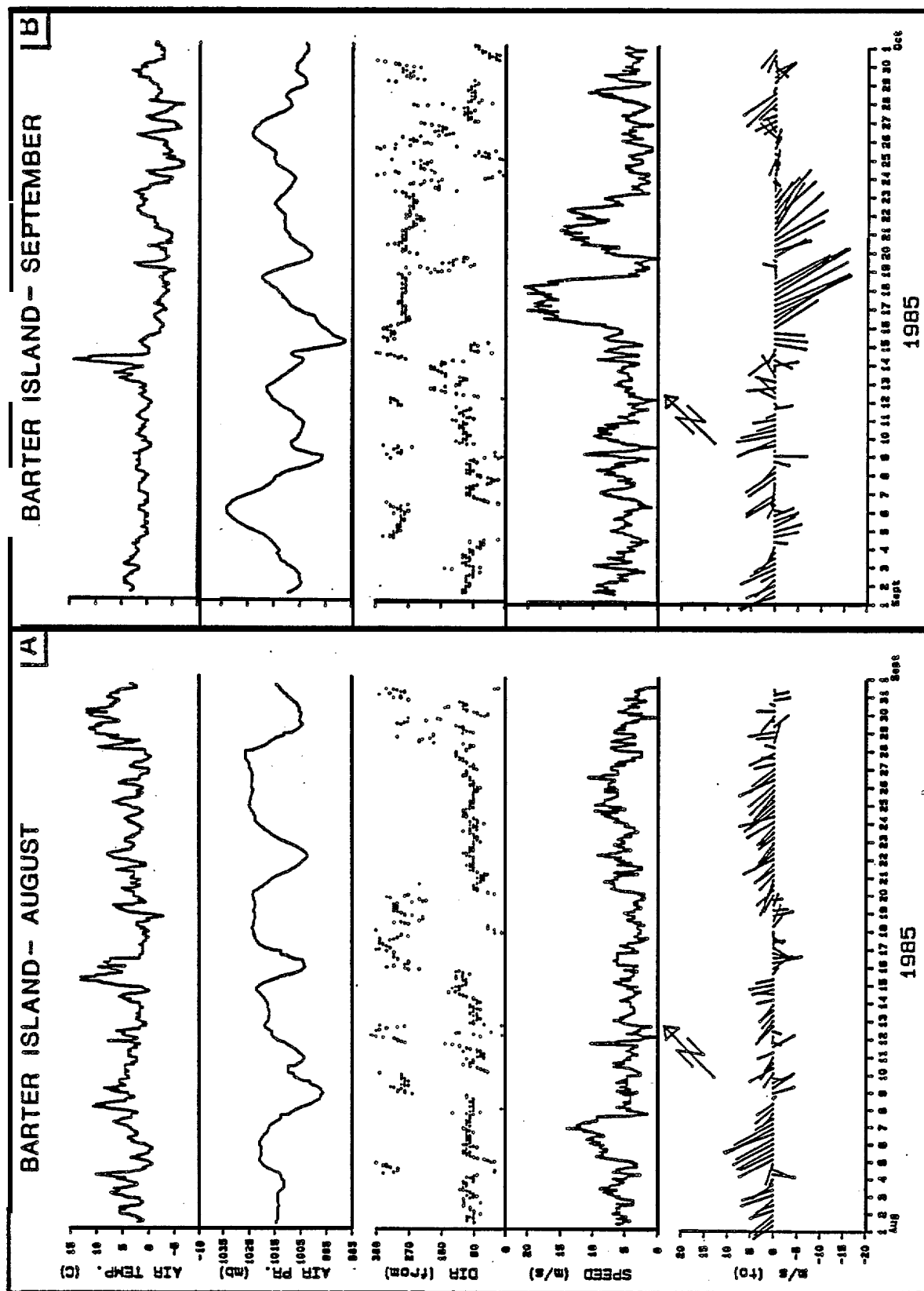


FIGURE 1. Meteorological observations from Barter Island, Alaska, in (A) August 1985, and (B) September 1985.

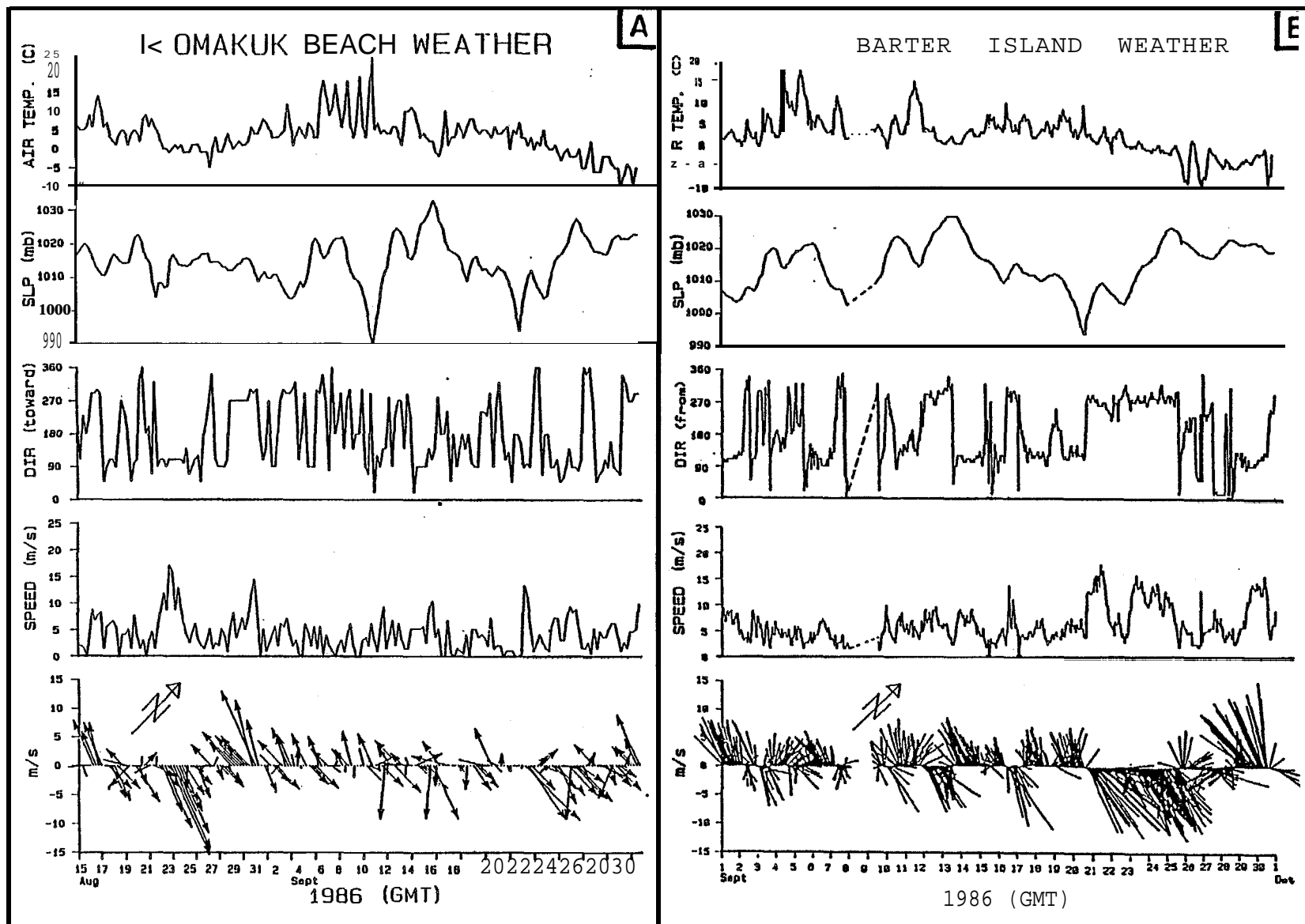


FIGURE 8. Meteorological observations from (A) Komakuk Beach, 15 August to 30 September 1986, and (B) Barter Island, 1-30 September 1986.

**Table 2.** Summary of available hydrological information available for major rivers flowing into **the Beaufort Sea**. Note **that** no information could be located for the Canning and Kongakut Rivers.

River	Longitude of Coastal Discharge	Drainage Area ( $10^3 \text{ km}^2$ )	Mean Annual Discharge ( $10^6 \text{ m}^3$ )	Estimated Discharge ( $\text{m}^3/\text{s}$ )	
				Maximum	late August
Colville <sup>b</sup>	150.5	?	1,000	?	?
Kuparuk <sup>b,c</sup>	149	8.1	?	2,000	80 -
Sagavanirktok <sup>c,d</sup>	148	5.7	?	550	150
Canning	145	?	?	?	?
Kongakut	141.8	?	?	?	?
Firth <sup>a</sup>	139*5	5.8	124	773	60
Mackenzie <sup>a</sup>	133-137	1,800	30,400	34,000	13,500

Information Sources:

<sup>a</sup> Environment Canada (1980) - **Histor. Streamflow** Summary to 1979, Yukon and N.W.T.

<sup>b</sup> Walker (1975).

<sup>c</sup> Carlson et al. (1977).

<sup>d</sup> Britch et al. (1983).

The **only** major **river that** drains directly into the study area is the Kongakut River. It is one of the smaller Alaskan rivers. Unfortunately, discharge measurements on the Alaskan rivers are sparse, making comparisons of mean and maximum discharge levels uncertain.

The Mackenzie River differs greatly from other rivers in the region in terms of the seasonal discharge cycle and **the total** volume discharged. The Mackenzie River drains a **very large** area including some **climatically** temperate portions of western Canada, while the drainage basins of the **other** rivers are located entirely in permafrost zones. As a result, a **large** proportion of the **total annual** discharge of the Alaskan rivers results from snow and ice melt during freshet. Walker (1975) estimated that 60% of the Colville River's annual discharge occurs during a 3-week period from late May to mid-June. By comparison, only 20 to 25% of the **total** discharge from the Mackenzie River occurs during the 3 weeks of maximum discharge from mid-May to late June. Because of this disparity in the seasonal discharge patterns, the proportion of freshwater input due to the Mackenzie River is even **larger** during the summer months than during the freshet period of late spring.

### Water Mass Characteristics

The water column of the Arctic Ocean can be divided into three layers, each defined according to a range of temperatures and salinities: the Arctic Water Mass (extending to depths of about 200 m); the Atlantic Water Mass (200 to 900 m); and the Arctic Bottom Water (900 m to **bottom**). These water masses are illustrated on a typical deep ocean profile (Fig. 9). As all three water

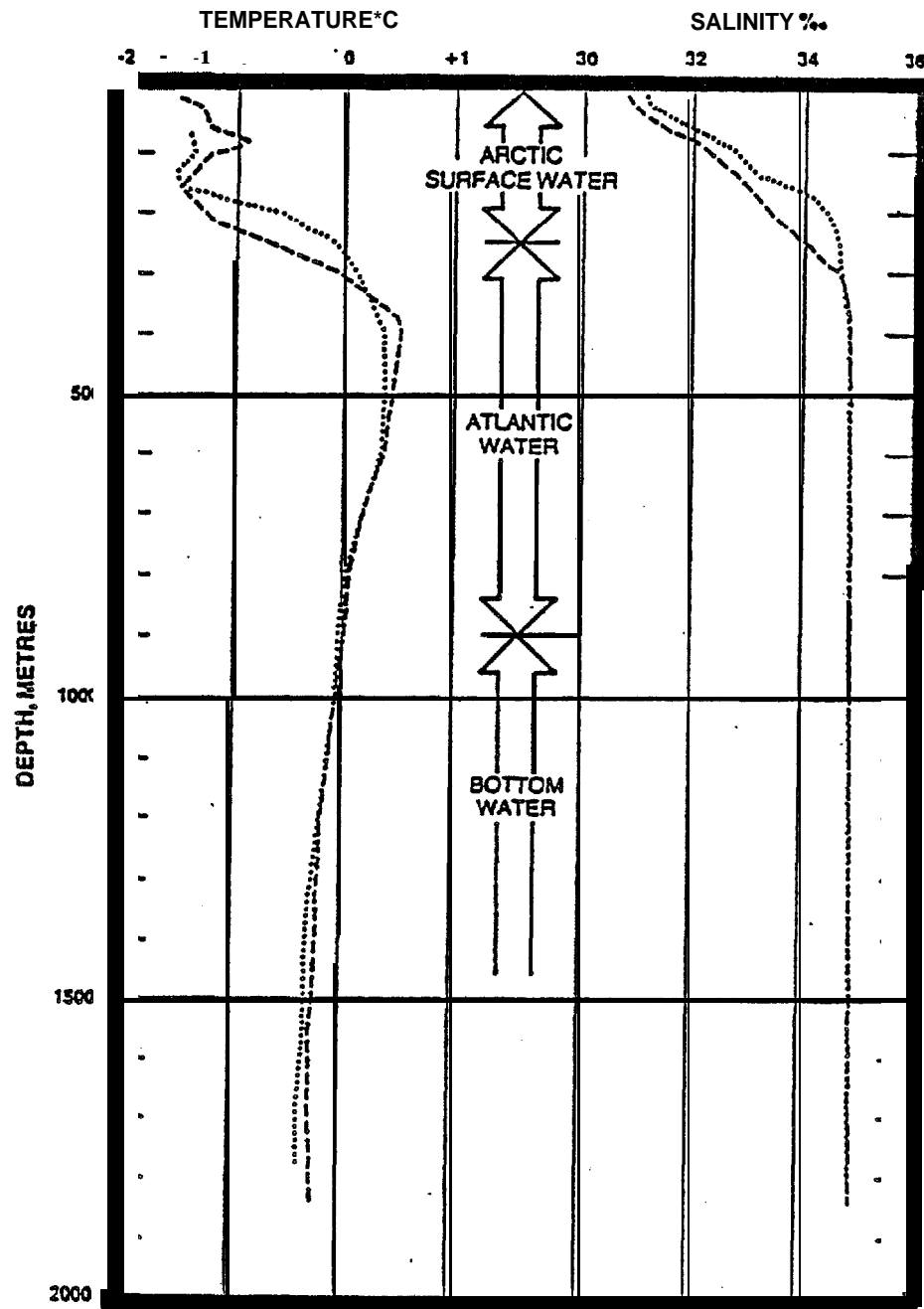


FIGURE 9 . Two typical vertical profiles of temperature and salinity in the deep water of the Beaufort Sea (after Milne and Herlinveaux, undated).



**masses** are **cold**, their densities are almost **solely** determined by salinity. **For** a vertically stable distribution, salinity must increase with depth although temperature can either increase or decrease. **In** this report, salinity is given in practical salinity units or **psu**. One **psu** is very nearly one part per **thousand**, **as** defined by Lewis (1981).

**The most** variable temperatures and salinities occur within the upper portion of the **Arctic** Water Mass, especially in areas **close** to shore. Far offshore where the ice retreats only briefly, if at **all**, the surface salinity is typically near **30 psu** and temperatures are near the freezing point of seawater (**-1.6°C** at **30 psu**). Over the continental shelf and in the nearshore **zone**, much **larger** ranges of surface salinities and Temperatures occur. Here, **the ice** can **retreat** for several weeks in summer allowing **solar** insolation and river **runoff** to affect surface water properties.

**The** greatest changes, relative to water in the offshore region, occur in **the** shallow lagoons inshore of the barrier islands. In July and August, surface Temperatures of **10°C** or more have been reported within coastal lagoons, with salinities 10-30 psu (Envirosphere 1984). Even **lower** salinities **occur** near river mouths during runoff.

**In** portions of the nearshore zone outside lagoons, the warm, fresher water occurs as a **thin** surface layer (typically 3-5 m deep). Beneath this **layer**, a sharp density interface **known** as a **pycnocline** separates the upper layer from **colder** more **saline** water with offshore temperature and salinity characteristics. As summer progresses, **the upper layer cools** and becomes more saline due to **mixing**, reduced **solar** insolation, and the reduced river and **air** temperatures. By **the** end of summer, the upper **layer** temperatures are generally **2°C** or less, and salinities **15 to 25 psu**. As ice begins to form **along** the coast, the salinity and temperature of the nearshore waters **return to those** of the offshore waters.

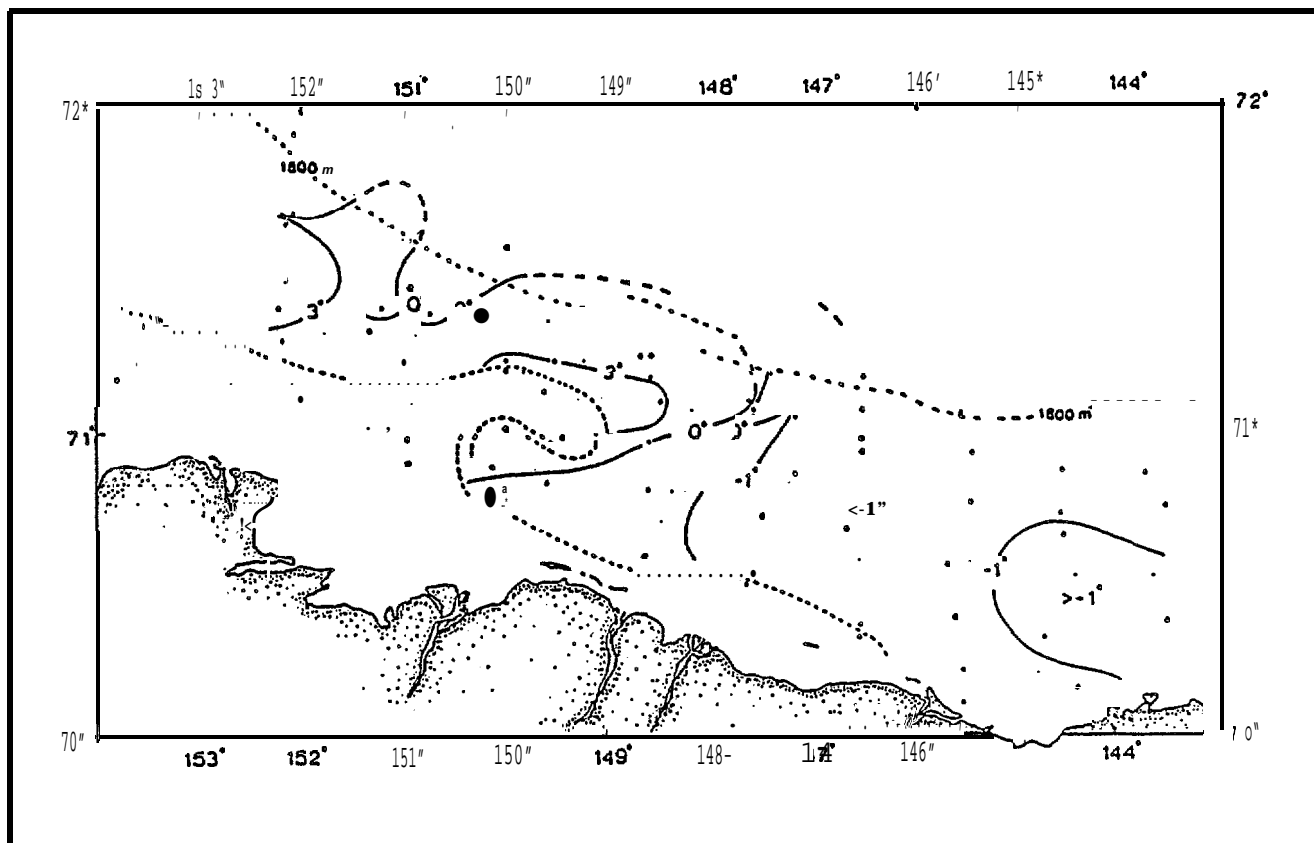
The ranges of salinities and temperatures in the Arctic Water Mass narrow with increasing depth in the water column. On the basis of the WEBSEC cruises (Western Beaufort Sea Ecological Cruise) of **1971-72** (Hufford et al. 1974), salinities at 5-30 m depths have a summer range of 25-31 psu. **In** winter, salinities generally increase **to 30-33 psu** due to the absence of ice **melt** and **land** runoff. Summer temperatures extend from the freezing point to **6°C** and **2.5°C** at 10 m and 50 m depths, respectively.

The decreasing variability of water properties with increasing depth makes it possible to detect **sublayers** of the Arctic Water Mass on the basis of their temperatures and salinities. These **sublayers** originate in adjacent seas **and** are advected into the western **Beaufort** Sea. **In** some cases, these **sublayers** may extend to **the** surface but **cannot be** detected due to the high spatial and temporal variability of the surface **layer**.

Mountain (1974) identified two Arctic Water Mass **sublayers** near the shelf **break** in the western Beaufort Sea. These **sublayers**, designated the Alaskan Coastal Waters and Bering Sea Waters, are warm--up to **5-10°C**. Salinities are 31.5 psu or less in the Alaskan Coastal sublayer and near **32 psu** in the Bering Sea Water. These water masses have been used as tracers of the coastal current that moves northeast past Point Barrow (Hufford 1973, 1974; Mountain

1974; Paquette and Bourke 1974). Estimates of the minimum eastward and inshore extent of this current may be made from Figure 10. Due to mixing with colder waters, Alaskan Coastal Waters and Bering Sea Waters **lose** their distinctive heat content as they are advected eastward. Within the Eastern Alaskan **study area**, they are often difficult to recognize (see 'Results: Subsurface Distributions'). The sublayers are summer phenomena. By late winter the elevated temperatures are generally completely eroded by heat diffusion and cooling of the water column, associated with ice growth.

**Upwelling** of subsurface water on the inner continental shelf **also** markedly alters the properties of shelf **water**. In particular, Hufford (1974) observed **that** strong east winds result in cooling and in raised salinity and nutrient levels in continental shelf waters. These changes reflect admixture of the continental shelf waters with the deeper waters of the continental slope (Fig. 11). **Upwelling** and other processes that modify water masses are discussed in more detail in the 'Results - Subsurface Distributions' subsection.



**FIGURE 10.** Temperature (°C) on the 1025.0 kg/m<sup>3</sup> density surface for **August 1972**. The **warm** core of water occurring **along** the continental slope, as indicated by the 3° and 0°C isotherms, originates in the Bering arid Chukchi seas. The dashed **line** near the coast represents the inshore limit of this water (from Mountain 1974).

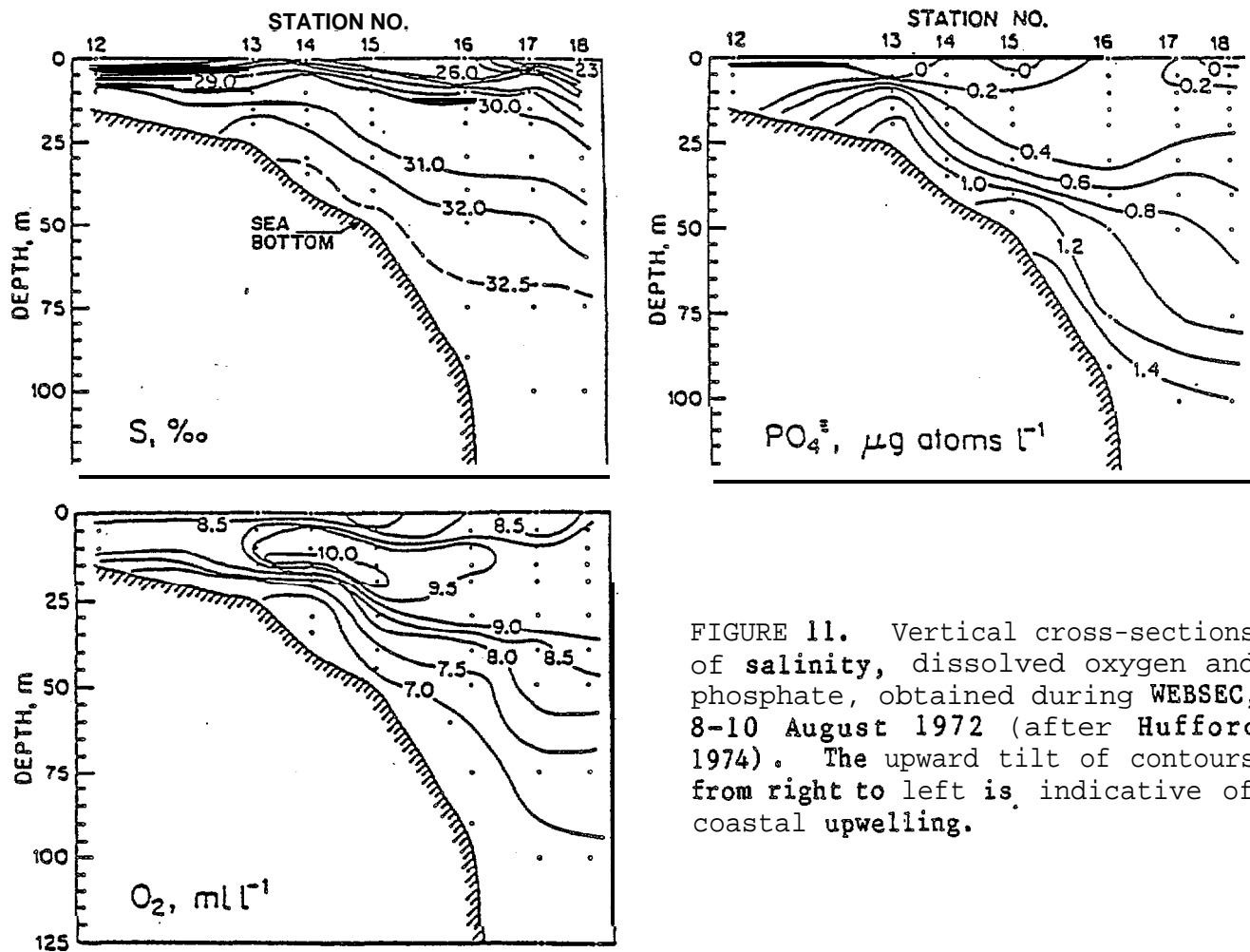


FIGURE 11. Vertical cross-sections of salinity, dissolved oxygen and phosphate, obtained during WEBSEC, 8-10 August 1972 (after Hufford 1974). The upward tilt of contours from right to left is indicative of coastal upwelling.

### Circulation Patterns

The circulation of the nearshore zone is dominated by local wind forcing. Current studies have been conducted within the nearshore zone in coastal embayments and lagoons along the length of the Alaskan coastline (e.g. Matthews 1979, 1981; Mungall et al. 1979; Britch et al. 1983), including one study in the Eastern Alaskan Beaufort Sea (Hachmeister and Vinelli 1984). The results consistently demonstrate that nearshore surface waters move at 2 to 4% of the surface wind speed during summer. This motion and its corresponding high variability are greatly reduced by the solid winter ice cover (Aagaard 1981). However, even in summer when the relationship between local winds and near-surface currents is clear, complicated current responses have been noted, particularly in areas of complex bathymetry and/or strong vertical stratification.

Farther from the coast, within the inner and middle shelf zone (depths 10-50 m), much less information on circulation is available due to inaccessibility from land bases and more variable ice conditions. The limited available data indicate that currents result primarily from local wind forcing. There have been no observations of any major circulation patterns that persist over time scales significantly in excess of wind durations.

The major residual, non-locally wind-driven surface circulation features of the western Beaufort Sea are a current that flows east past Point Barrow, roughly following the shelf-break, and westward currents farther offshore associated with the Beaufort Gyre (Fig. 12). The eastward current, dubbed the **Beaufort Undercurrent** by **Aagaard** (1984), begins as a strong flow northward from Bering Strait and along the eastern edge of the **Chukchi Sea** (Fig. 12). The Beaufort Undercurrent appears to be associated with the eastward advection of Bering Sea Water along the shelf edge, described above, but the Undercurrent extends much farther east, having been measured regularly in the Canadian Beaufort Sea east to **129°W**. Near the mouth of Barrow Canyon the flow turns east following the inner edge of the continental slope. This east current contains plankton characteristic of the Pacific Ocean (Johnson 1956) and it also has salinities characteristic of the Pacific. **Hufford (1973)** found evidence that these eastward flows extended beyond **156°W** in 12 out of 17 years, and in some years may have **reached Barter Island (143°W)**. Calculations based on water mass data (**Mountain 1974**) indicated that speeds of this flow ranged up to 50 cm/s just north of the shelf break.

More recently, subsurface current measurements have been made over the outer shelf and continental slope (depths 60-225 m) between **146°W** and **152°W** (**Aagaard and Haugen 1977; Aagaard 1981**). Results from current meters at depths of 34 m or more indicated the usual alignment of the currents with the **local** bathymetric contours and the occurrence of relatively strong flows in both directions. Net flows were increasingly eastward at increasing depth. Typical mean speeds were 10 cm/s for depths in excess of **100 m**, but were much reduced near the surface due to the effects of the prevailing easterly winds. Large depth-independent **flows** having speeds over 40 cm/s sometimes occur over periods of several days.

Farther offshore, the flow is dominated by the clockwise circulation of the Beaufort Gyre in the Canadian Basin of the Arctic Ocean (Fig. 12). This gyre is centered near **75°N, 145°W**, near the mean high of atmospheric pressure, and the driving force is believed to be the mean wind field (Campbell 1965; Gait 1973). The mean drift speed of the gyre is 2 to 3 cm/s westward over the **abyssal plain** of the Canadian Basin, based on the calculations of **Kusunoki (1962)** and **Newton (1973)** and the ice drift observations of **Sater (1969)**. The speed of the **gyral** movements can be larger, particularly at the periphery where the gyre extends over the outer portion of the continental slope. **Newton (1973)** estimated that flow speeds can reach 5 to 10 cm/s at the southern **rim** of the gyre over the western Beaufort Sea.

#### Tidal Heights and Currents

The astronomical diurnal and semi-diurnal tidal heights and tidal currents are small in the Beaufort Sea. The tides are mixed, mainly semi-diurnal in composition, with mean ranges of 10 to 30 cm (**Aagaard et al. 1978**). Tidal currents are correspondingly weak: **Aagaard (1978)** reports tidal currents over the inner continental **slope** of 2 to 4 cm/s for the **M<sub>2</sub>, S<sub>2</sub>, K<sub>1</sub>** and **O<sub>1</sub>** constituents. On the inner shelf, **Aagaard and Haugen (1977)** reported weaker tidal flows with no constituents having amplitudes in excess of 2 cm/s.

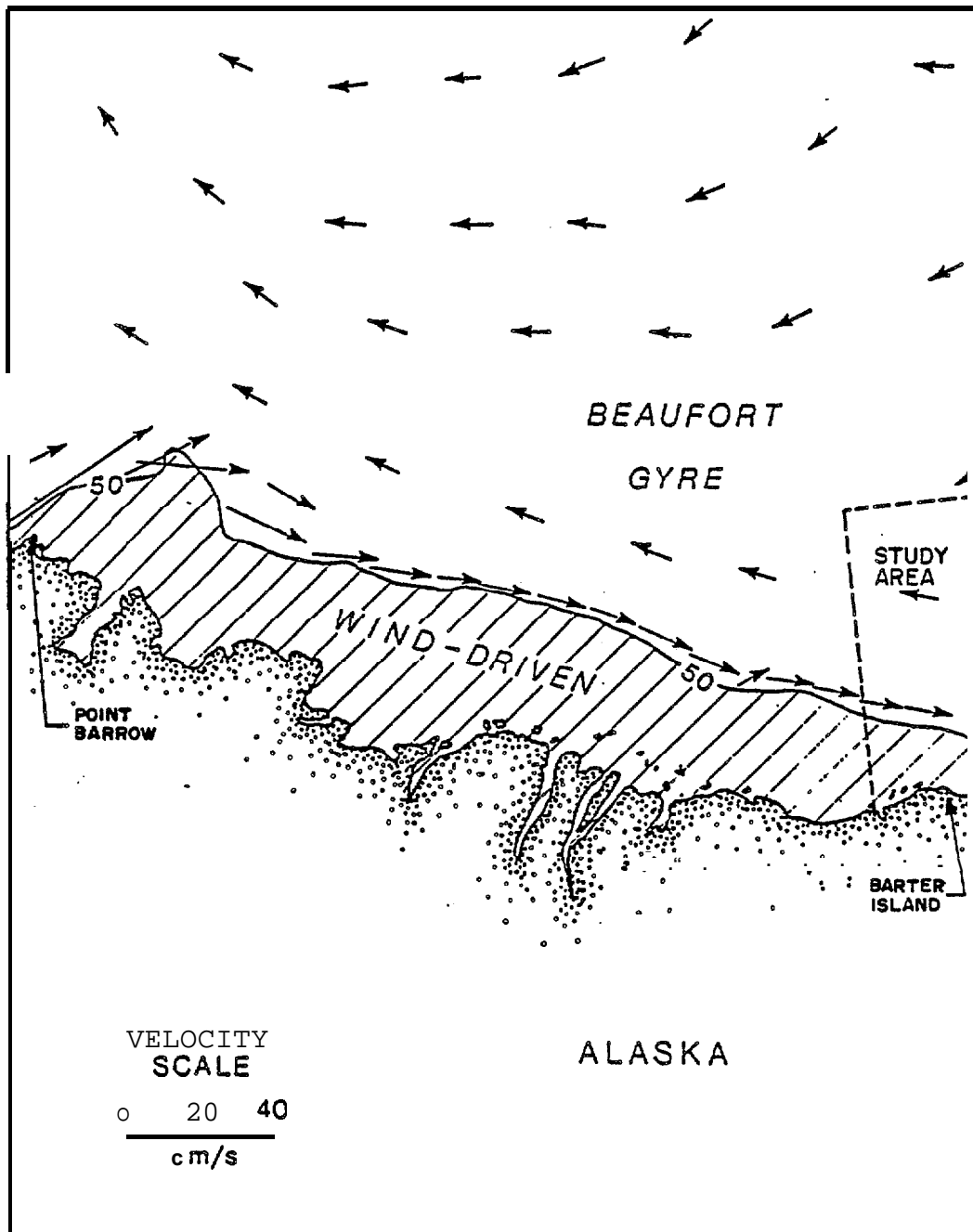


FIGURE 12. Major circulation features of the Alaskan Beaufort Sea, including the eastward-flowing Beaufort Current and the westward-flowing Beaufort Gyre.

**Tidal** currents can be considerably stronger under special circumstances within the study area. For example, at the constricted entrances to lagoons, tidal **flows** of 50 cm/s have been measured (**Hachmeister** and **Vinelli** 1984). Internal waves can also **result** in stronger flows at semi-diurnal tidal periods (or shorter periods). These can occur in areas **where** ice melt or river runoff produces thin, fresh layers overlying denser seawater.

#### Methods, 1985-86

##### Airborne Remote Sensing

Survey Procedures,--The airborne remote sensing instrumentation was mounted in the Twin Otter aircraft chartered **by** the project in both 1985 and **1986**. The equipment was used during **bowhead** surveys **only** during the first half of September, when the study area was almost entirely ice free. The increase in ice concentrations during the middle of September, particularly in 1985, would have limited the effectiveness of airborne remote sensing of water characteristics in the latter half of September.

The instruments measured water temperature and water color at the surface below the aircraft. The water **color** data provided information about both turbidity and chlorophyll content (details given later). Data on water temperature and **color** were acquired in three situations:

1. Most systematic data were acquired during four stratified random surveys to determine the distribution and number of bowhead whales in the **study** area during early-mid September of 1985-86. The standard route consisted of 13 transects oriented **NNE-SSW** from the shore to the 200 m depth contour (average spacing 10.6 km), plus eight N-S transects between the 200 and 2000 m "depth contours (average spacing 18.5 km). Figure 25 on p. 60, shows the transect locations. In **1985**, the first survey was on 5-6 September (nearshore lines **only**, due to persistent fog offshore); the second was **on 12-13** September. In 1986 the two surveys were on 4-5 and **11-15** September.
2. On several dates each year, the aircraft flew **along** the broad-scale transects being occupied by the boat on those days (see **Fig. 16** on p. 40). The primary purpose was to calibrate the airborne instruments against temperature, chlorophyll and secchi measurements obtained from the **boat**. On 6 September **1986** the aircraft flew **along** three **NNE-SSW** transects in the Canadian **Beaufort** east of Herschel Island, where the **M.V. 'Ivik'** was making oceanographic transects (Bradstreet et al. **1987**). These lines provided calibration data in warmer and more turbid waters than were present in the Eastern Alaskan **Beaufort** Sea.
3. On some other occasions while the aircraft searched for whales for purposes of behavioral observation and photogrammetry, the remote sensing instruments were used. Occasionally a **small** grid of transects was flown over and near a concentration of feeding whales. These 'non-systematic' data were used to examine inshore oceanographic features on 4-6 and 10 September 1986.

Airspeed was 200 km/h while the aircraft flew along' transects. Aircraft altitude was **153 m** during the 5-6 September 1985 survey, 305 m during **all** - other systematic surveys, and 153-457 m on other occasions. Observers aboard **the** aircraft noted sea state, ice conditions, and visible **water mass discontinuities**. Aircraft position was recorded frequently using a **GNS 500A VLF** navigation system, Airborne remote sensing data were sometimes acquired under overcast conditions (**e.g.** 5-6 Sept 1985; **4, 7, 9, 11** Sept 1986) when satellite **remote** sensing was impossible. This technique **also** provided water **color** measurements of much greater sensitivity than did the satellite,

Water Color Sensing. --The water **color** measurements derived from the aircraft were made with a custom **built** research spectrometer **using** techniques developed by and for the Canadian Department of **Fisheries and Oceans** at 'the Institute of Ocean Sciences, Sidney, B.C., Canada (**Neville and Gower 1977; Borstad et al. 1981; Borstad and Cower 1984; Borstad 1985; Fissel et al. 1986**). For a **complete** description of the theory of the measurements and of the instrument, the reader is referred to these publications and the references therein.

Reflectance spectra calculated every **1 to 8** seconds (longer under heavy overcast skies) were corrected for a mean atmospheric scattering contribution appropriate **to** the 'aircraft altitude, and for an additive signal from surface reflection, mist and whitecaps. The latter additive signal was assumed **to be white**. Its magnitude was calculated on the assumption that the corrected reflectance at 780 nm was **zero**. The continuous computations of **the** various chlorophyll and turbidity **indices**, corrected as **just** described, were plotted against time on strip charts. The data were **later** transferred to maps.

The acceptance angle of the spectrometer is **small** (**0.17° x 0.7°**) and from 150 m altitude its instantaneous footprint on the sea surface is about 0.44 x 1.8 m. However, this is smeared by the forward **velocity** of the aircraft (about **55 m/s**). Hence, 'the survey data are for narrow strips 50 **to** '400 m **long**, depending on the integration **time** and aircraft ground speed.

On the maps of water **color** and temperature as derived from airborne remote sensing data (**e.g.** Fig. **23**), **isopleths** were drawn between adjacent transects to connect areas with similar values. We attempted to present the data with similar spatial resolution in the along-shore and offshore directions. Hence, some small-scale features (**<1-2 km**) evident **along** single or adjacent transects were not mapped, since features of this size occurring between transects could have been missed.

The remote color measurements need to be calibrated using in situ measurements. Surface chlorophyll data from the 1985 boat-based **sampling** indicated that chlorophyll **a** **levels** were **below 1 mg/m<sup>3</sup>** almost everywhere, and **below 0.5** at most **locations**. The **only** values above **1 mg/m<sup>3</sup>** were within a few kilometers of shore off **Kaktovik**. Similarly, **the** Fluorescence Line Height (**FLH**) index from the airborne remote sensing indicated that **chlorophyll** concentrations were low everywhere. Hence, **the color** variations that we observed were caused largely by **variations** in amount of suspended inorganic materials rather than chlorophyll. Surface reflectance at a wavelength of 640 nm (**R640** index) has been used in previous studies (**Borstad 1985; Fissel et al. 1986**) as a measure of suspended organic materials. A **relationship** between

R640 and **secchi** transparency was evident from the 1985 and 1986 data (Fig. 13). Because the number of simultaneous measurements was small, all comparisons for which good aircraft data were available are shown, including some for which the time interval between the two measurements is as long as 48 hours. We assume that for most of the study area, horizontal **advection** and real spatial variability are responsible for disagreements between the two measurements. The vertical bars indicate the variability in the airborne data within 20 s (approximately 1 km) on either side of the location of the boat-based measurement.

The factors most limiting the amount of good quality **data** were the **low sun angle** in September, the rapidly changing illumination **late** in the day, and the very low reflectance over most of the study area. It was not possible to **do** all flying at mid-day, when conditions for airborne remote sensing were most favorable. Although visibility sometimes was **still** adequate for **whale** observations until sunset, the noise on the spectrometer increased **rapidly** after about 17:00 local solar time. At sun elevations below about 10-15°, the fraction of the incident light entering the water prior to reflection decreases, and for any given particle content the signal returned to the spectrometer is greatly decreased. The combination of an increase in the surface-reflected component and the decrease in **signal strength usually** prevented collecting useful data after about 17:30 local solar time on clear days. On heavily overcast days, conditions usually became unacceptable after about 16:00 h.

When flights extended to sunset, the **last** portion of the data was unusable. In **most** cases the survey flights were made from east to west and the area north of Barter Island was surveyed latest in the day. Measurement problems in that area were compounded because the water there was clear with **low** signal levels.

Airborne' Radiation Thermometer.--Sea surface temperature was measured using a Barnes 'Precision Radiation Thermometer **PRT-5**, a commercial radiometer that measures the 10-12 micron thermal infrared radiation from the ocean using a chopped, temperature stabilized thermistor. The instrument has a 2° **field of view**, and therefore an instantaneous footprint of about 5 m diameter **from** 150 m altitude and 10 m from 300 m altitude. **Its** practical accuracy is about  $\pm 0.5$  Co.

Comparisons of the radiometer data **with** sea surface temperatures (SST) measured from the boat are presented in Figure 14. In 1985, a line **with** the same slope as the **lab** calibration fits the 6 September data to within about  $\pm 0.25$  Co. Most boat-based data collected at **other** times (5, 7 and 8 Sept), when plotted against radiometer data from the same **places** on 6 September, **also fall** near the **line**; this suggests that there was relatively little change in the geographic pattern of temperatures during this period. No **boat-based** temperature data were available at the time of the 12 and 13 September 1985 aerial survey. We used the calibration line shown in Figure 14 for those days **also**, although we expect larger errors because of different atmospheric conditions. In 1986, measured SST was well correlated with the radiometer values from corresponding **places** and times (Fig. 14) but the radiometer signal resolution was reduced due to instrument problems. In 1986, useful temperature data were obtained on 4, 5, 6, 10, **11**, 14 and 15 September.



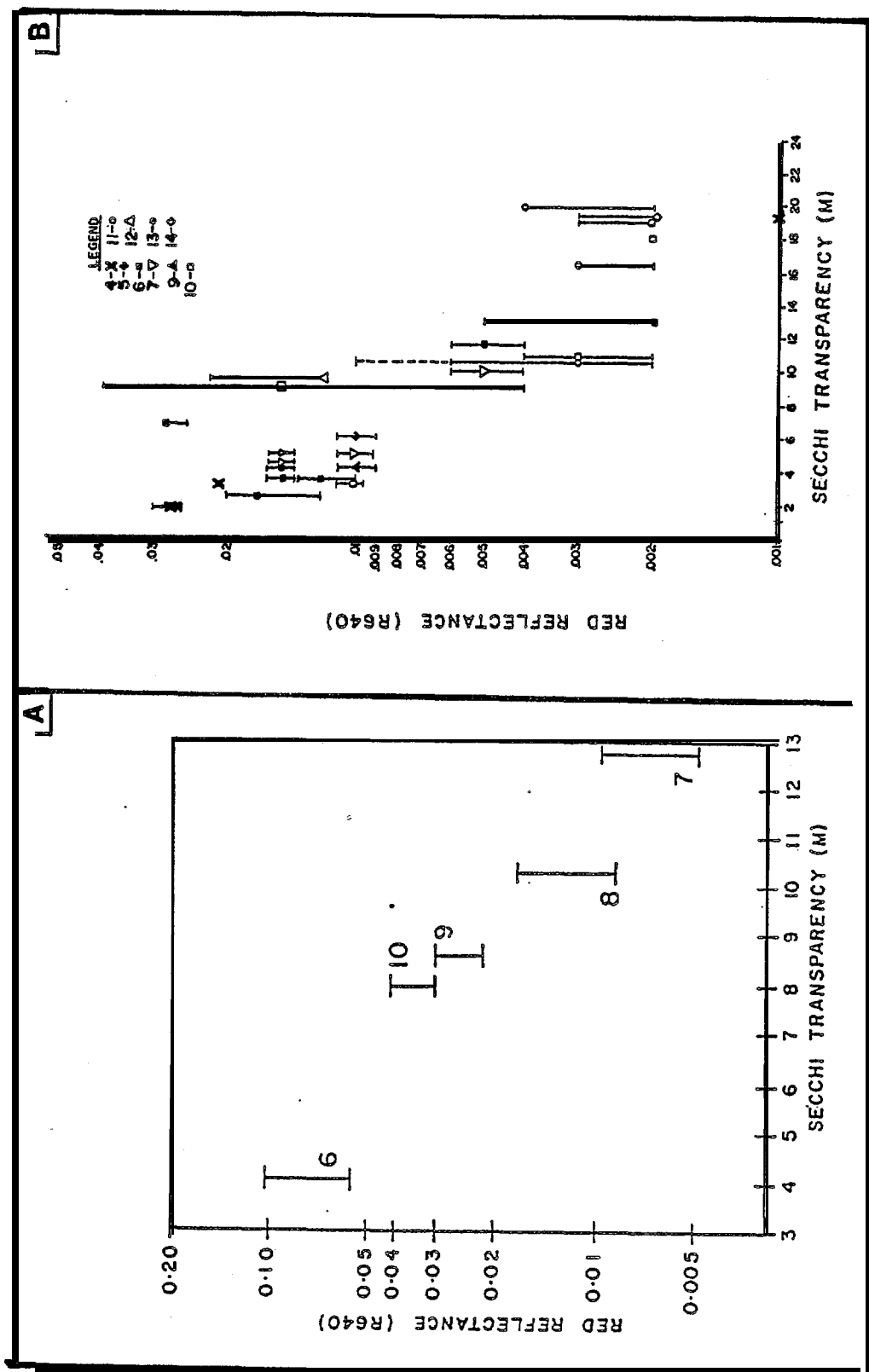


FIGURE 13. Airborne observations of the Red Reflectance (R640) Index vs. measurements of secchi transparency made at the same locations on (A) 7 to 10 September 1985 (numbers are station numbers along boat transect 2 - see Fig. 16A); and (B) 4 to 14 September 1986 (numbers are the days in September).

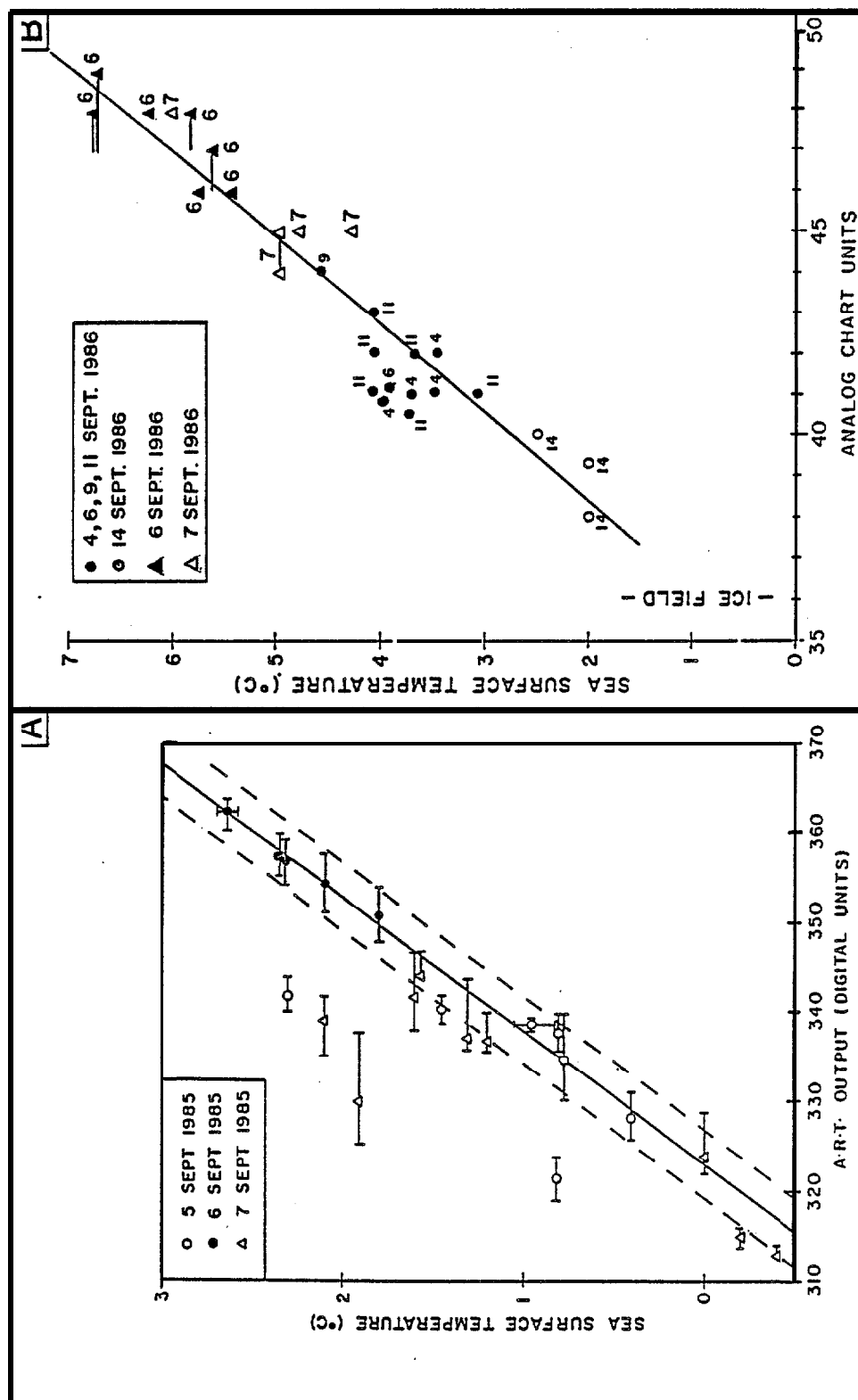


FIGURE 14. Airborne Radiation Thermometer (ART) measurements vs. in situ sea surface temperatures (SST) at the same locations and at approximately the same times. (A) ART measurements (digital units) made 6 September 1985 from 150 m altitude vs. in situ SST, 5-7 September 1985. The calibration curve (solid line) is drawn parallel to the laboratory calibration but with a vertical offset to take it through the boat-based measurements from 6 September. The horizontal bars indicate the range of ART output for 2 km segments along the flight line. Each segment is centered on the position of the in situ observations along boat transects 1 and 2 (Fig. 16A). The dashed lines are  $\pm 0.25^\circ\text{C}$  from the fitted line. (B) ART measurements (analog chart units) made on 4-14 September 1986 vs. in situ SST measurements from the 'Annika Marie' (circles) and the 'Arctic Ivik' (triangles). Solid symbols represent same-day pairs; open symbols show pairs with more than 24 hour time separation.

## Satellite Data

General Description of Satellite Data Types and Sources.--More extensive synoptic views of the overall distribution of surface water temperature and **turbidity** were obtained from images produced by the Advance-d Very High Resolution Radiometers (AVHRR) on the polar-orbiting NOAA series of satellites [NOAA-6, 7, 8 or 9). These images are obtained in digital computer-compatible tape form in each of five separate bands within the wavelength range 580-12,500 nm. As transmitted by the satellite, images consist of arrays of **10-bit** numbers representing the instrument's response to radiation. Each value represents the radiation from a pixel or picture element. A pixel is the minimum-resolvable portion of the earth's surface, and for a NOAA satellite is about 1.2 km<sup>2</sup> in area. Each image consists of successive scanning lines or strips aligned perpendicular to the projection of the satellite orbit onto the earth's surface. Each strip contains 2048 pixels. One image is formed for each band of wavelengths sensed by the satellite.

Ideally, the two NOAA satellites normally in operation allow the observation of events on time scales as short as a few hours. Each satellite passes over the study area at least 2-3 times per day during daylight hours, and each pass covers a wide swath (2500 km). In cloudy areas such as the Beaufort Sea, usable imagery is not obtained nearly this often, and only one image per day is routinely archived. However, the availability of numerous daily overpasses greatly increases the likelihood of obtaining data from any particular area during occasional periods of clear viewing.

In this study, we used images obtained in bands 1 and 4, which correspond to visible wavelengths (580-680 nm) and 'thermal' infrared wavelengths (10,500-11,300 nm), respectively. Band 1 radiance levels (energy per unit time per unit area) are primarily associated with scattering of solar radiation from the uppermost portion of the ocean. Because band 1 reflectance is approximately proportional to the concentration of light-scattering particulate in the upper portion of the water column, band 1 AVHRR images can be used to estimate surface turbidity levels.

Radiances in band 4 and in the other 'thermal' infrared wavelength bands (3 and 5), on the other hand, are mainly attributable to energy radiated by the sea surface, as opposed to scattering of solar energy. Hence, the radiance in these bands is closely related to sea surface temperature.

Digital images either used or considered for use in this study were obtained from five sources:

1. Environmental Data Information Services (EDIS), U.S. Dept. of Commerce, Capitol Heights, Maryland;
2. The Arctic Weather Centre, Atmospheric Environment Service, Edmonton, Alberta;
3. National Environmental Satellite Data Information Service (NESDIS), Field Station, Gilmore Creek, Alaska;

4. The Prince Albert, Saskatchewan (PASS), receiving station of the Canada Centre for Remote Sensing;
5. The Remote Sensing **Centre** of the University British Columbia (UBC), Vancouver, British Columbia.

As part of the initial literature review phase of this study, eight satellite image pairs from **late** August and September of 1980-84 were **selected** and analyzed (**Fissel** et al. 1985). Two of these images (26 Aug **1983** and 13 **Sept** 1984) have been reprocessed and are presented below.

For 1985, four pairs of images are considered here (**Table 3**). Although additional images **would have** improved our ability to follow events, the availability of three images from the particularly cloudy month of September 1985 was fortuitous. The images were obtained during two easterly wind events (28 Aug; 13 **Sept**) and after two westerly wind events (18 and 22 Sept).

For 1986, six pairs of NOAA-9 satellite imagery (**Table 3**) were analyzed, although **only** four are presented completely in the report. The earliest image, for 26 August 1986, was obtained immediately following the passage of a major northwesterly storm; most of the study area was obscured by **cloud**. **Clouds** persisted until 6 September when data were obtained throughout virtually all of the study area. Good viewing conditions persisted on 8 and 10 September. Throughout the first ten days of September 1986, winds were weak and variable, and **blew predominantly** from the **east**. Following a brief period of moderate **west-** and northwest winds on 12-13 September, another good satellite image was obtained on 14 September. Following periods of west winds

Table 3. Satellite imagery used in this report. The imagery was obtained from the **Gilmore** Creek field station of the National Environmental Satellite Data Information Service (**NESDIS**), the Remote Sensing **Centre** of the University of British Columbia (**UBC**), and the Prince Albert, Saskatchewan, receiving station (PASS).

Satellite	Orbit	Date	Time	Source
NOAA-7	<b>11206</b>	26 Aug <b>1983</b>	<b>21:21Z</b>	PASS
NOAA-8	16640	13 Sept 1984	<b>23:09Z</b>	UBC
NOAA-9	3660	28 <b>Aug</b> 1985	<b>21:35Z</b>	<b>UBC</b>
NOAA-9	3886	13 Sept <b>1985</b>	<b>22:20Z</b>	<b>UBC</b>
NOAA-9	3956	18 Sept 1985	?	<b>UBC</b>
NOAA-9	4013	22 Sept <b>1985</b>	<b>22:10Z</b>	<b>NESDIS</b>
NOAA-9	8781	26 Aug <b>1986</b>	<b>22:07Z</b>	UBC
NOAA-9	8936	6 Sept <b>1986</b>	22:03Z	<b>UBC</b>
<b>NOAA-9</b>	8964	8 <b>Sept</b> 1986	<b>21:14Z</b>	UBC
NOAA-9	8992	10 Sept 1986	<b>21:19Z</b>	UBC
NOAA-9	8992	14 Sept 1986	<b>22:17Z</b>	<b>UBC</b>
NOAA-9	9218	26 Sept 1986	<b>21:50Z</b>	UBC

during the passage of major storms from 20 to 25 September, the final 1986 satellite data were obtained on 26 September.

Methods of Satellite Data Analysis.--The digital tape images were processed using the facilities of the Imaging Processing Laboratory at the Institute of Ocean Sciences, Sidney, B.C., in a manner similar to that described in previous studies of bowhead whale habitats (Borstad 1985; Fissel et al. 1986; Thomson et al. 1986). These facilities allow the production of computer graphic representations of the matrix of radiance values associated with individual surface pixels in each distinct wavelength band. The correct position of each pixel was established on an equirectangular projection using image rectification programs and recognizable coastal landmarks. The absolute geometric accuracy is estimated as approximately 2 km. In addition to the Eastern Alaskan study region, the rectified area included Mackenzie Bay (east to 136°W) because of the influence of water from the Mackenzie River on surface waters within the Eastern Alaskan Beaufort Sea.

Our image processing procedure involved the combined use of the Band 1 and Band 4 images to identify pixels whose high radiance values in both bands indicated obstruction by cloud and/or ice. (Note: high radiance values in bands 1 and 4 correspond to high values of turbidity and to cold temperatures, respectively. In contrast, dark or low radiance areas on these band 1 and 4 images are associated with clear and warm water, respectively.) Pixels containing ice or cloud were depicted in white on the resulting color images. Land areas were depicted in black and a latitude-longitude grid was superimposed. Pixel radiances in open-water cloud-free areas were represented as 6 color-coded categories. As in earlier studies (Thomson et al. 1986), the magnitudes and ranges of variation of the band 1 radiance in the studied areas were only about 15% of the corresponding band 4 quantities. As a result, surface spatial details were most clearly extracted from the thermal infrared data. To display these details, we often prepared two maps from the same band 4 data. One map used 6 colors to represent the range of band 4 variation across the entire region that we examined (Mackenzie Bay plus the study area). The second map provided a finer subdivision of the range of band 4 values within the Eastern Alaskan Beaufort Sea. For the data obtained at two day intervals on 6, 8 and 10 September 1986, the temperature (band 4) data were presented in a special display showing the continental shelf portion of the study area (Fig. 33 on p. 73). A much finer subdivision of the range of band 4 values was used to show small scale surface features within the inshore portions of the study area, where whales were feeding and zooplankton was being sampled during the same period.

Calibration of the Satellite Imagery.--In 1986, calibration of the satellite data was facilitated by the extensive set of boat-based oceanographic measurements obtained from 4-19 September in this study. Further oceanographic measurements were available from the bowhead food availability study being conducted concurrently in the Canadian Beaufort Sea, off the Yukon coast (5-8 Sept 1986, Bradstreet et al. 1987). In 1985, the available oceanographic data were much less extensive, and complete calibration of the satellite data was not possible.

Direct **measurements** of temperature and turbidity (as indicated by **secchi** depth values) were obtained within several hours of the times of the 6, 8, 10 and 14 September 1986 imagery. Through comparisons of the boat- and satellite-based data (Fig. 15), calibration formulae were derived for the temperature (band 4) and turbidity (**band 1**) satellite measurements. For temperature, a linear dependence of pixel level on sea-surface temperature was assumed; the linear fit was derived through a least squares linear regression algorithm from 13 data **values** obtained on 6, 8 and 10 September 1986. Only oceanographic data obtained within 6 h of the satellite pass were used in computing the regression **line**. In both the 10 and 14 September imagery, a systematic bias was inferred for both the band 1 and band 4 "measurements, corresponding to the widespread occurrence of a light haze. Prior to calibration the band 4 data were corrected by subtracting 13 bits from the data, equivalent to an upward temperature shift of approximately 1.5 Co. The accuracy of the temperature measurements derived from satellite data is estimated to be  $\pm 1.0$  Co for the 6, 8 and 10 September imagery. For other 1986 imagery and all pre-1986 data, temperature uncertainties could be larger due to the lack of sufficient simultaneous calibration data.

Band 1 satellite data were compared with boat-based **secchi** depth measurements to derive a calibration curve (fitted by eye). The band 1 satellite data provided low sensitivity for detecting changes in turbidity within the study area, where most **secchi** depth measurements were 3 to 20 m, corresponding to a range of only 4 bits in the band 1 values. The accuracy of the band 1 (visible) satellite data in estimating **secchi** depths is roughly  $\pm 3$  m at secchi depths exceeding 5 m, and  $\pm 1$  m for more turbid waters having secchi depths of 5 m or less.

#### Boat-Based Data, 1985

The primary physical oceanographic data collected from the boat in 1985 were temperature-salinity (T/S) measurements along three transect lines. Frequent surface T/S measurements were acquired using a Hydrolab 4021, and a lesser number of vertical profiles were obtained with an Applied Microsystems CTD-12.

Surface T/S Data, 1985.--Measurements of surface temperature and salinity were obtained from the vessel 'Annika Marie' at 67 stations along three transect lines (Fig. 16A). The Hydrolab 4021 employs a thermistor for temperature measurement and a 4-electrode conductivity cell. Conductivity measurements are automatically and internally adjusted to produce values referenced to 25°C. The manufacturer provides the following estimates of accuracy: temperature,  $\pm 0.2$  C°; conductivity,  $\pm 2.0$  mmho/cm, using the 200K scale.

Surface measurements were obtained during three distinct intervals. On 5-6 September 1985, 29 sets of observations were collected along transect 1. On 7-10 September 1985, 27 sets of observations were obtained on transect 2. Eleven additional sets of observations were collected along transect 4 on 18 September 1985.

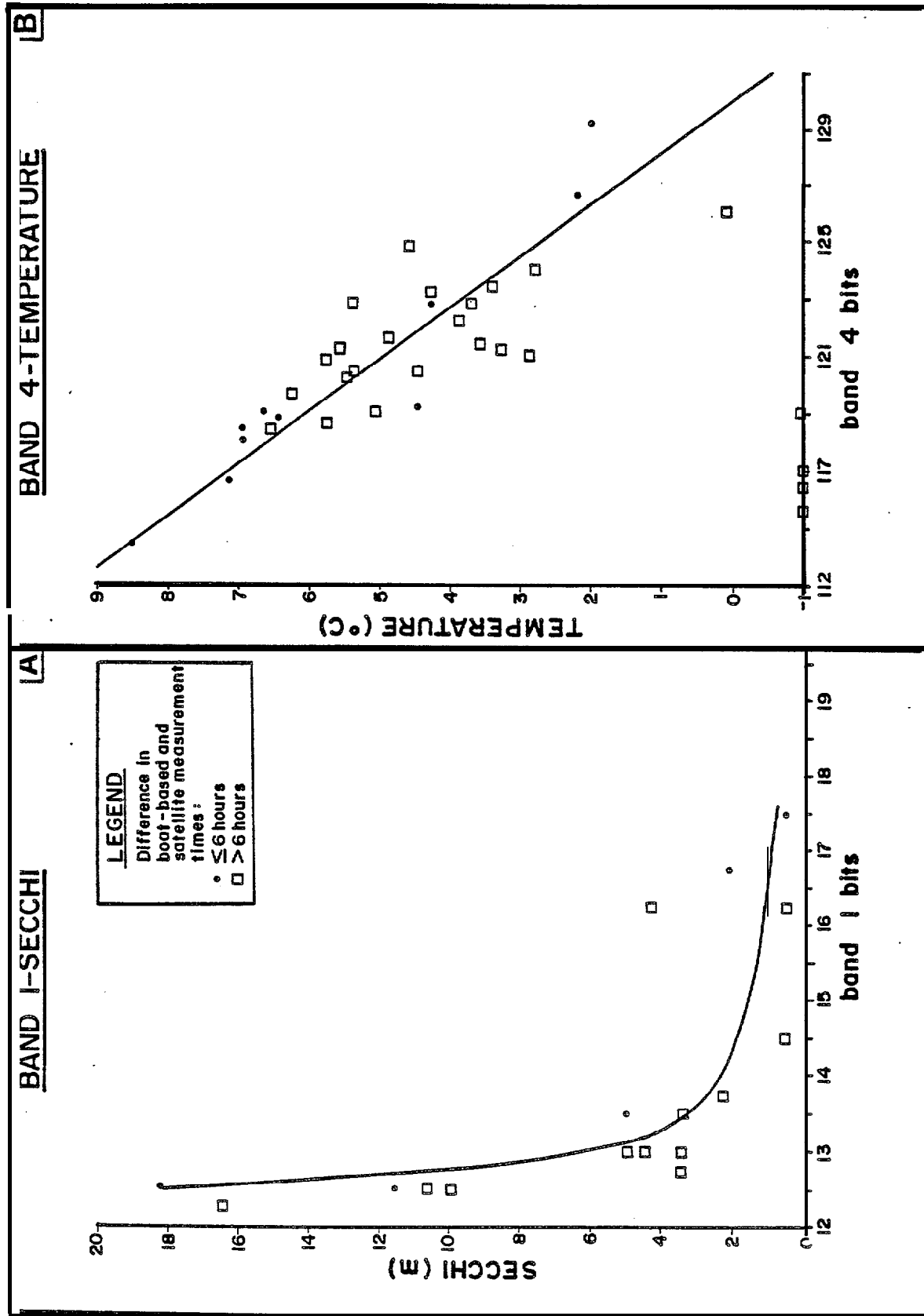
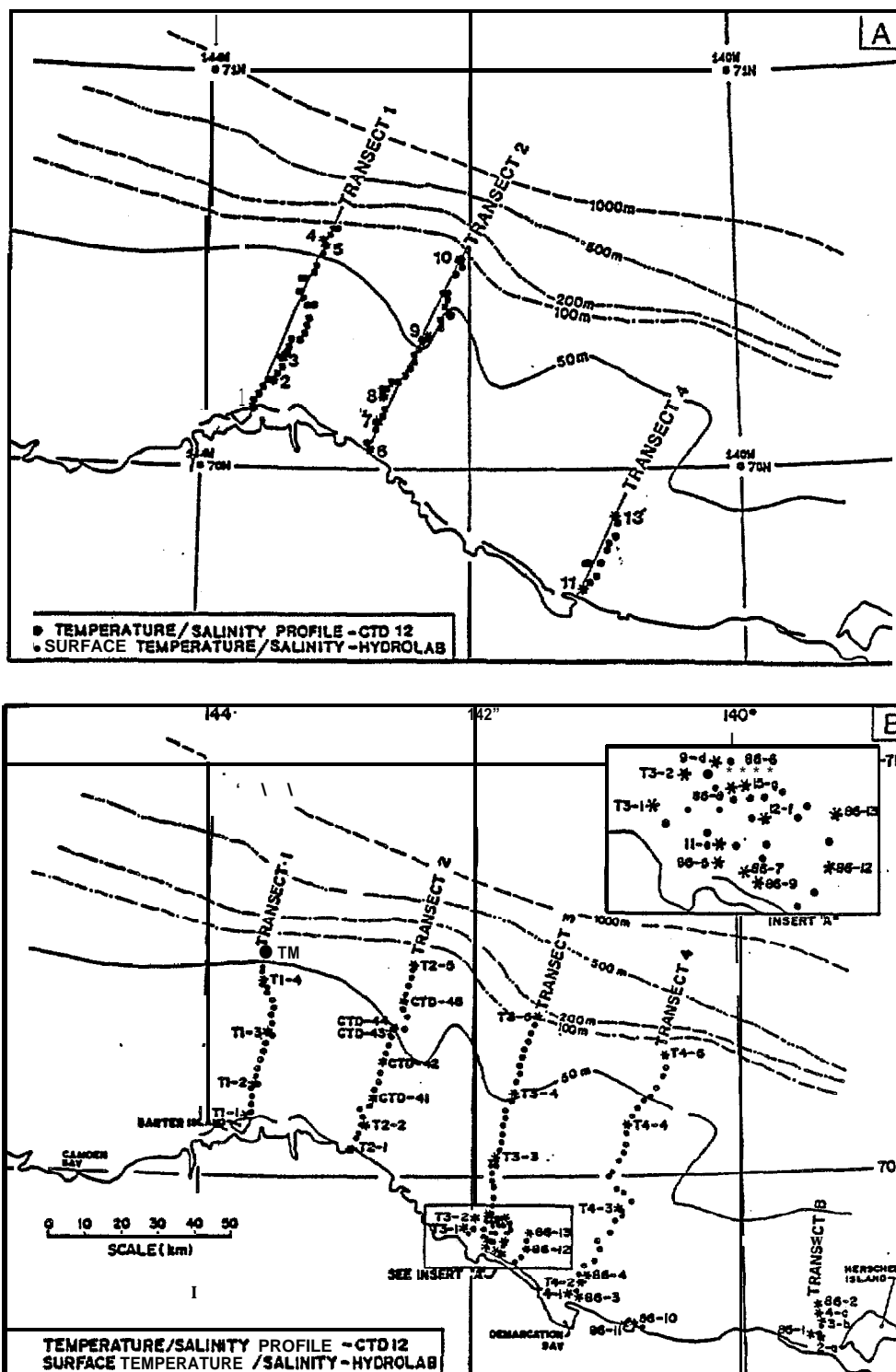


FIGURE 15. AVHRR band 1 and 4 satellite output vs. boat-based surface secchi and surface temperature measurements in 1986. In both cases, the satellite output units are given on the 8-bit resolution scale. All 1986 satellite data used in this study provided 10-bit resolution.



**FIGURE 16.** Locations of temperature and salinity measurements obtained (A) in 1985 along boat transects 1, 2 and 4 (5-6 Sept, 7-10 Sept and 18 Sept), and (B) in 1986 along boat transects B, 1, 2 3 and 4 (4 Sept, 16-17 Sept, 18-19 Sept., 12-14 Sept, and 9-11 Sept). Also shown in (B) are inner shelf measurement locations occupied from 4-7 September 1986.



Surface water samples collected from the boat. were **later** analyzed on a **salinometer**. Comparison of these salinities with those obtained by the **Hydrolab** indicate that the **Hydrolab** readings were consistently too **large** by **1.55 to 1.85 psu** (Fig. 17A). Consequently, all surface salinity **data** from 1985 presented in this report have been reduced by **1.7 psu**. No similar check was possible for the **Hydrolab temperatures**, but most values agreed to within  $\pm 0.5\text{ }^{\circ}\text{C}$  of the surface temperatures from the **CTD-12** profiles (**Fissel et al. 1986, p. 31**). In view of the large time delay between measurements from the two different instruments, the agreement was considered satisfactory and **likely** within the expected accuracy of both instruments.

T/S Profiles, 1985.--Vertical profiles of **temperature** and salinity were made at **13** stations in 1985 (Fig. 16A), although the **station 12** data were **unretrievable**. The Applied **Microsystem CTD-12** records internally on magnetic tape using five channels (**Pressure, Temperature, Conductivity, Temperature, Conductivity**), repeating sequentially. Each measurement requires 0.56 s, with each 5-channel scan taking 3 s. Vertical separations between successive temperature and conductivity measurements range from 0.1 to **1.0 m**, according to the lowering rate of the instrument.

The data were transferred to the Arctic Sciences Ltd. **PDP 11/24** computer for processing. Obvious spikes were removed through manual editing of the data. **Only** the data obtained from the downcast, which has the **best** sensor response, were used for each site. Interpolated values of pressure and **temperature** were computed so that **all** data, including conductivity, represent the same depth during each raw data scan. The raw values were then converted into engineering **units** (Pressure - **dbar**, Temperature -  $^{\circ}\text{C}$ , Conductivity ratio), applying calibration data obtained on 16 March 1984. **The** pressures were then adjusted so that the initial readings of each cast occurred at **1 dbar**. Salinities were computed using the Practical Salinity Scale 1978 (Lewis 1981). Sigma-t, or reduced density, was calculated (**Millero and Poisson 1981**) as

$$\text{Sigma-t} = (\text{density} - 1) \times 10^3.$$

Sound speed and the freezing point temperature (**Millero 1978**) were also computed.

The manufacturer provides the following estimates for the accuracy of the **CTD-12**: temperature,  $\pm 0.02\text{ }^{\circ}\text{C}$ ; conductivity,  $\pm 0.03$  psu equivalent salinity. **No** reversing bottles were used for **field** checks on the calibration. The surface temperature data of the **CTD-12** and the **Hydrolab** generally agreed to within  $\pm 0.5\text{ }^{\circ}\text{C}$ . **No** check was possible for salinity data as the surface samples collected for laboratory **salinometer** determination were not collected at the same time as the CTD profile. From previous experience with the **CTD-12**, the resolution may approach  $\pm 0.03$  psu; however, the accuracy is typically on the order of  $\pm 0.1$  psu.

#### Boat-based Data, 1986

Surface T/S Data, 1986.--Measurements of surface temperature and salinity were obtained from the vessel '**Annika Marie**' at 156 locations in **total**, including 112 sites located on the four broad-scale boat transects occupied in 1986 (Fig. 16B). Data were obtained from 4 to 19 September 1986. **The** instrument, a **Hydrolab** model TC-2, displayed the **data** on a **panel meter**. The

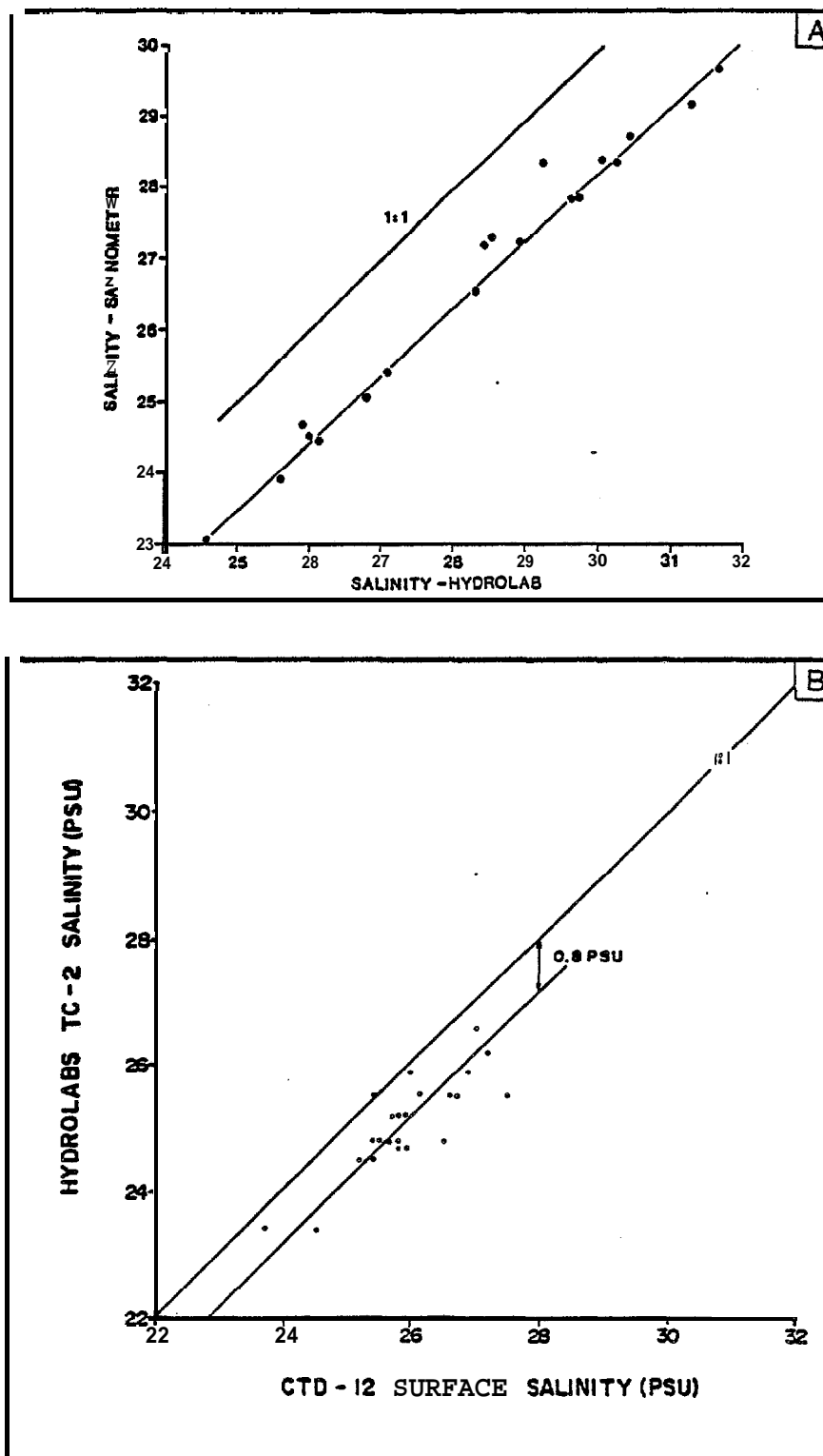


FIGURE 170 Calibration data for surface salinity measurements. (A) Comparison of 1985 salinity measurements derived from the Hydrolab unit aboard the boat with those of bottle samples measured using a laboratory salinometer. The Hydrolab unit provided readings that were high by approximately 1.7 psu. (B) Comparison of 1986 salinity measurements from the Hydrolab TC-2 unit with the corrected values from the Applied Microsystems CTD-12 instrument. The TC-2 unit was reading high by approximately 0.8 psu.

expected accuracy of the unit is  $\pm 0.2$  C° Temperature and  $\pm 2.0$  mmho/cm, using the 0-100K scale.

Comparisons of the raw Hydrolab measurements with the surface readings from the more accurate Applied Microsystems CTD-12 instrument (after correction to surface water sample data - see below) indicated that the Hydrolab temperature data were reading low by  $0.1$  C°. Comparison of the salinity values computed from the Hydrolab data with the corrected CTD-12 values revealed that the Hydrolab readings were systematically low by  $0.8$  psu (Fig. 17B). Corrections of  $0.1$  C° and  $0.8$  psu were applied to the Hydrolab temperature and salinity data, respectively.

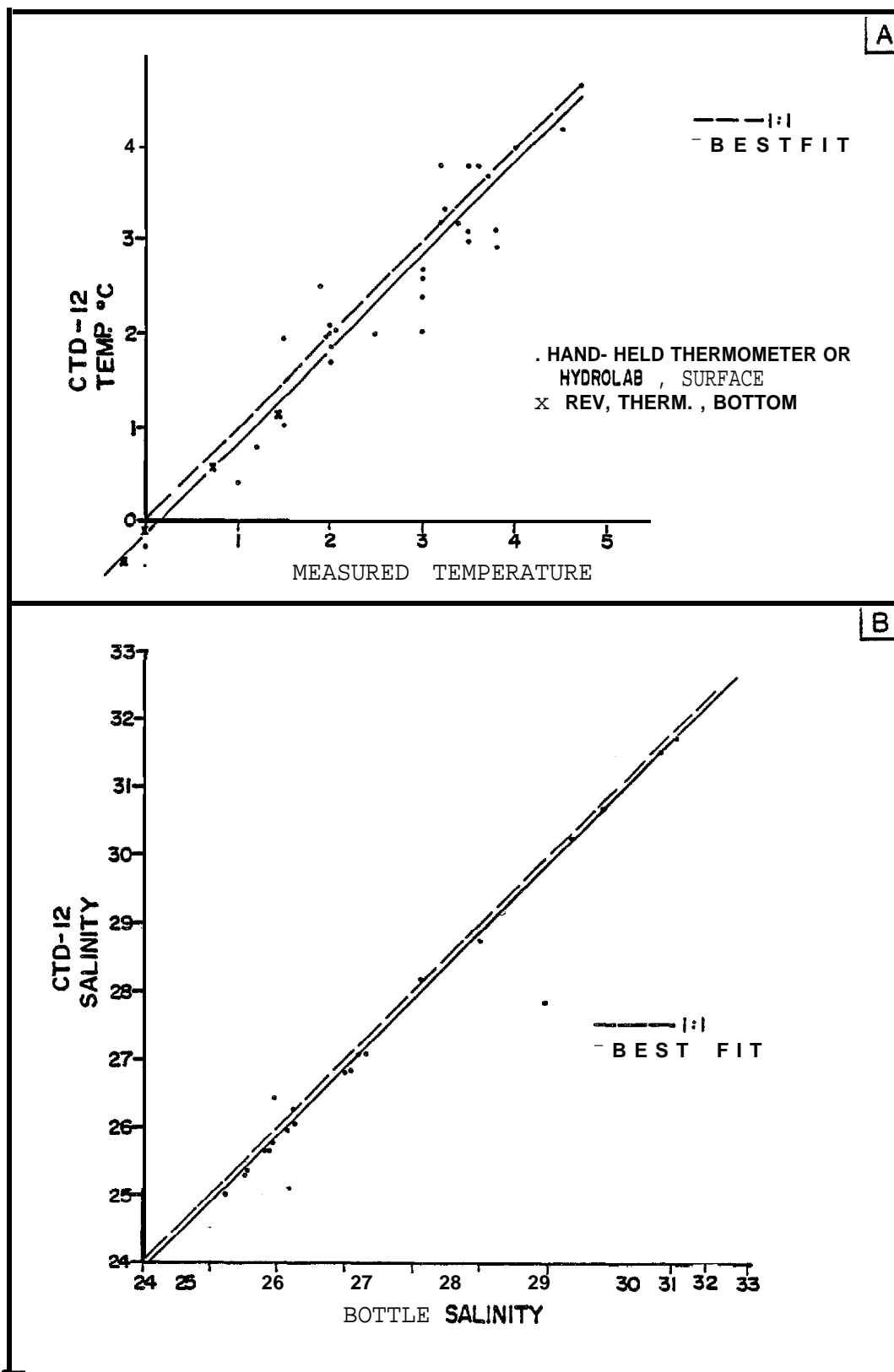
T/S Profiles, 1986.--Vertical profiles of temperature and salinity were obtained at 45 stations using an Applied Microsystems CTD-12, the same unit as used in 1985. The raw values were converted into engineering units by applying calibration coefficients obtained 27 June 1986. The pressures were adjusted so initial readings at each cast occurred at approximately 1 dbar. Temperatures from the CTD-12 were compared with surface values obtained using a hand-held thermometer or the Hydrolab, and with near-bottom values from the reversing thermometer (Fig. 18A). The CTD-12 values were all increased by  $0.2$  Co so that these temperatures better agreed with those obtained by the other methods. Using the corrected pressure and temperature values, and the unadjusted conductivities, salinities were computed using the Practical Salinity Scale 1978 (Lewis 1981). When compared with the salinities of the water bottle samples, measured on a laboratory salinometer, the CTD-12 salinities were lower by approximately  $0.1$  psu (Fig. 18B). Accordingly,  $0.1$  psu was added to all the CTD-12 salinity values.

Unfortunately the temperature range of the CTD-12 was limited to a minimum of  $-0.35$ °C, and a special procedure was developed to derive estimates of temperature and salinity for these measurements (see below). For data above  $-0.35$ °C, we estimate the resolution and accuracy of the CTD-12 to be  $\pm 0.02$  and  $\pm 0.2$  C° for temperature, and  $\pm 0.03$  psu and  $\pm 0.1$  psu for salinity.

Estimation of Temperature and Salinities at Depth, 1986.--Because the CTD-12 did not measure temperatures less than  $-0.35$  Co, direct measurements of temperature were limited to the uppermost 8 to 20 m of the water column at most stations. Salinity data are also not directly available since salinity is a computed quantity, requiring measurements of temperature as well as conductivity ratio and pressure (or depth). The last two quantities were available at all depths from the CTD-12 data.

A small number of direct temperature and/or salinity measurements were obtained at depths exceeding 20 m, through the use of reversing thermometers and salinity determinations from bottle samples. These measurements were obtained at 11 stations from 12-19 September. Where only a temperature or salinity measurement was available for a particular depth, the other quantity could be computed.

A procedure was developed to provide estimates of temperatures and salinities at depths in excess of 30 m from the CTD-12 conductivity ratio data along with historical values of salinity at depth. First, the variability of temperature and salinity at depth for the summer in the Eastern Alaskan



**FIGURE 18.** Comparisons of the temperature (°C) and salinity (psu) measurements obtained in 1986 with the Applied Microsystems CTD-12 with concurrent measurements of (A) temperature using a reversing thermometer and (B) salinities measured on a laboratory salinometer from water samples collected from the boat.

Beaufort Sea was examined using **the** extensive measurements of **the** 1971-1972 WEBSEC program (at locations **east** of **145°W**; Hufford et al. 1974), the 1985 data set of the present study, and the available reversing thermometer and bottle salinity data from 1986. From these data (Fig. 19), **the** variability in salinity was found **to** be comparatively **small** at depths of 50 m or greater; **typical** standard deviations were **0.3 psu** or **less**. Moreover, **the** 1986 salinity data appeared **to follow** the historical salinity data closely at depths of 35 m or greater (with two notable exceptions where the water **column** was vertically uniform and the deviation can be explained as the effect of vertical mixing from a **lesser** depth). The temperature data showed larger relative variations **than** for salinity. In particular, **the** 1986 reversing thermometer data showed temperatures considerably warmer (by **0.3 to 1.0 Co**) **than** the averages from historical data.

From the comparisons described above, estimates of temperature and salinity were computed as follows:

1. Salinity was assumed to have the following values, determined from the historical data:

Depth (m)	Salinity (psu)	Depth (m)	Salinity (psu)
30	<b>31.50</b>	<b>100</b>	<b>32.30</b>
<b>40</b>	<b>31.65</b>	<b>125</b>	32.40
50	<b>31.90</b>	<b>150</b>	32.50
60	<b>32.10</b>	<b>175</b>	32.50
75	32.20		

However, these assumed values were modified if (1) **direct** bottle-derived salinity data were available; or (2) the conductivity ratio was vertically uniform **to** a considerably **lesser** depth; if so, a reduced salinity reflecting mixing of **less saline** water from above was applied.

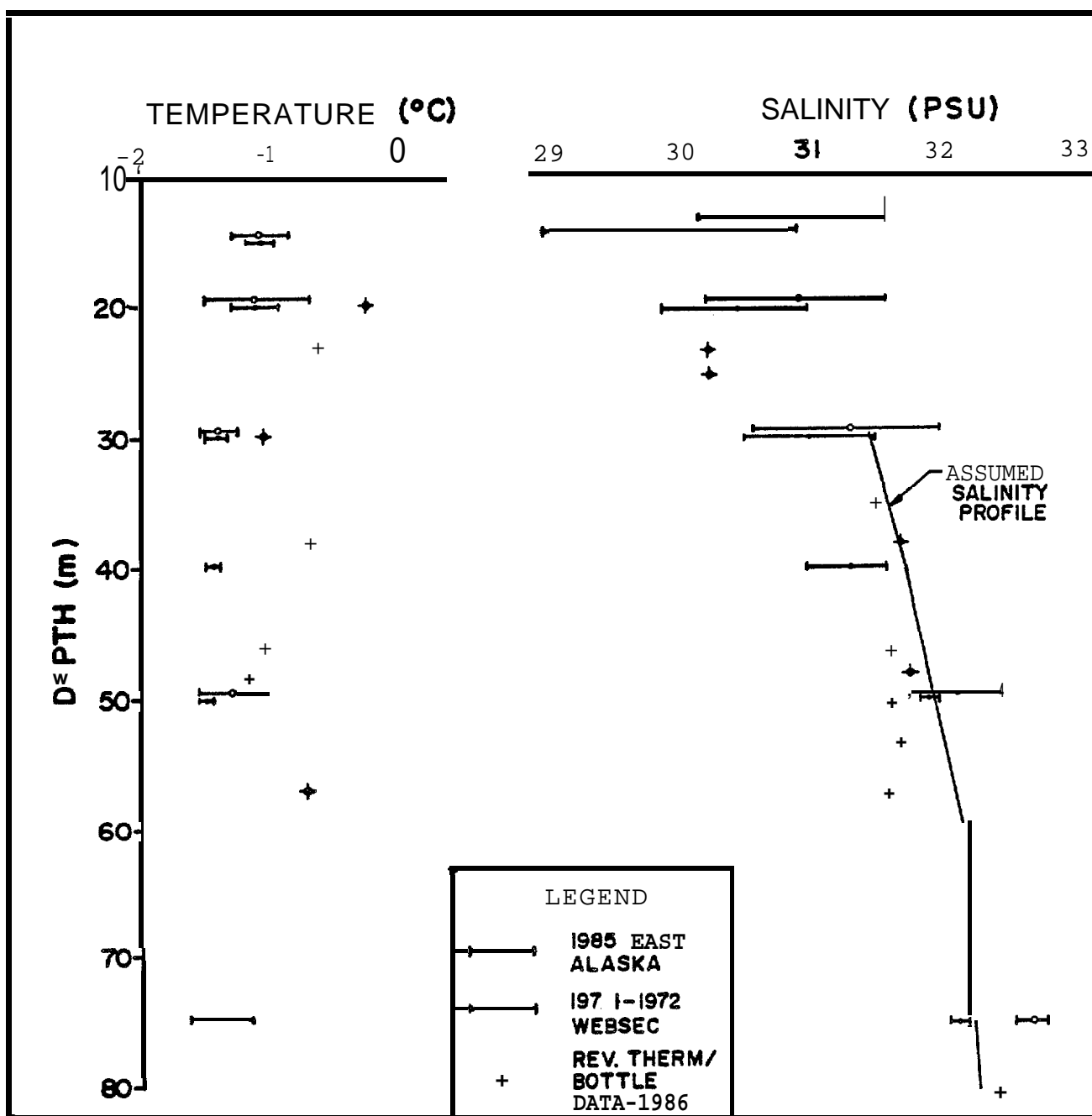
2. The temperature was computed from the assumed salinity **value** and the conductivity **ratio**, measured via the CTD-12.

This procedure is estimated **to** be accurate **to** within **0.7 psu** at depths of 30-50 m, and **0.5 psu** at depths >50 m. The **equivalent temperature** uncertainties are **estimated** as 0-.8 and 0.55 C°.

## Results

### Broad-Scale Surface Distributions

In **this** section, the surface distributions of water properties **within** the study area are presented and described, using NOAA satellite imagery (11 data sets, 1983-1986) and airborne remote sensing data (4 data sets, 1985-1986).



**FIGURE 19.** Vertical profiles of temperature and salinity derived from historical oceanographic data (Hufford et al. 1974), and the 1986 measurements derived from reversing thermometer and water bottle samples. These data were used to derive an assumed salinity profile for estimation of temperature and salinities from the CTD-12 data, at depths exceeding 30 m where temperatures were  $< -0.35^{\circ}\text{C}$ .

In **this** section, emphasis is placed on describing broad-scale distributions--surface oceanographic features having **scales** upwards of **3 n.mi.** (5 km). Water property distributions having smaller spatial scales are discussed **later** in 'Inshore Fine-Scale Oceanographic Features' and 'Frontal Characteristics'

26 August 1983.--On satellite images from **this** date, much of the southern and central portion of the study area was visible. There were weak southeast winds following a 2-day period of moderate westerlies. Unfortunately, much of the prominent northwestward extension of Mackenzie Bay water **lay** under the clouded portion of **the** image. The high concentrations of sea ice **west** of **Kaktovik** may have **strongly** influenced water characteristics **in** the western portion of the study area.

The band 1 data (Fig. 20A) were notable for their near uniformity. Small pockets of clearer water were evident along the coast west of Herschel Island and near **70°30'N, 142°30'W.**

The band 4 data (Fig. 20B,C) revealed colder temperatures **on** the Alaskan and Yukon shelves and **just** east of Herschel Island relative to water farther **east** in Mackenzie Bay. Warm water extended west to **141°30'**, and north to **70°30'**. Farther west, a tongue of much colder **water** was located just beyond **the** continental **shelf**, oriented along a NW-SE axis. This tongue of **cold** water **likely** represented **scattered** ice **floes** and associated very **low** surface temperatures extending southeast from the **loose** pack ice located north of **71°N**, as shown in the 25 August 1983 ice chart (Thomson et al. 1986, p. 70).

13 September 1984.--The images of this date were obtained **during** a period of strong east and southeast winds. **Cloud** limited detailed observations to the southern portion of the study region and adjoining Canadian waters (Fig. 21). Throughout the visible parts of the study area, surface waters were comparatively **clear** and cold. **In** contrast, much **warmer**, more turbid water was present **in** Mackenzie Bay. A 20 km wide tongue of the warm turbid **water** extended northwest **along** the outer edge of the **Yukon** continental **shelf** to **139°30'W.** The western edge of the tongue of Mackenzie Bay water was characterized by strong temperature and turbidity fronts extending over approximately 60 km.

Slightly elevated surface temperatures occurred just beyond the edge of the continental **shelf**, near the 200 m **isobath**, over most of the study area (Fig. 21C). Peak temperatures there were about 1.5 to 2 **C°** warmer than those over the continental **shelf** proper, but were at **least** 3 **Co** cooler **than** those in the core of the Mackenzie Bay **water** east of the study **area.**

28 August 1985.--The 28 August satellite imagery was recorded just prior to **the** start **of** the **field** study. Warm, silty water of Mackenzie Bay **origin** occurred as a broad band commencing some 55 **km** off the coast of northeastern Alaska (Fig. 229). These warm waters were advected northwest along the **outer** edge **of** the continental **shelf** from Mackenzie Canyon. The core of the warm Mackenzie Bay water (**pixel levels** <115) was present west to **142°15'W.** Slightly **cooler** water (but **still** comparatively warm, **pixel levels** of 116-124) extended over nearly the **full** width of the study **area.** The unusually **large** northwest extension of Mackenzie Bay water was associated with the extended

duration of easterly **winds** in 1985 (Fig. 7 on p. 21), combined with heavy ice cover to the east in the Canadian Beaufort Sea.

A coastal band of cold water was present over the inner shelf portion of our study area; the average width of this band was about 25 km (Fig. 22B,C). The offshore edge of this band abutted a body of intermediate temperature water. That water contained several large eddies over the outer half of the eastern Alaskan continental shelf, closely approaching the coast at 140°W as an intrusion **of** warmer water onto the inner portion of the continental shelf at that longitude.

The strongest gradients within the Alaskan study area occurred over the continental slope, with a progressive reduction **in** intensity westward, away from the influence of the Mackenzie River. Within the Alaskan study area, a weak and more diffuse thermal gradient, bordering the inner side of the intermediate-temperature surface water, was evident at offshore distances of about 25 km in the west to 35 **km** in the east.

5-6 September 1985.--On 5 September, the southeast corner of the study area (south of 70°N) was surveyed by aircraft; fog prevented surveys elsewhere. On 6 September, the remainder of the continental shelf (depths to 200 m) was surveyed (Fig. 23). These data were collected under **cloud**, 'so no usable satellite imagery was available.

**While** the large-scale distributions of water properties were similar to those on 28 August (**cf.** Fig. 22), surface temperatures exceeding 1.5°C occurred within 15 km of Demarcation Bay. The inferred shoreward movement of warm offshore water is consistent with onshore **advection** driven by the moderate northwesterly winds of 4-5 September 1985.

The airborne survey revealed a nearshore band of water warmer than 0°C within 2-3 km of the coast over the **full east-west extent** of the study area (Fig. 23A). This 'slightly warmer, turbid nearshore band was not evident **in the** satellite images (e.g. Fig. 22) because it was effectively **below** the 1-2 km spatial resolution of the NOAA satellite imagery. The nearshore band was visually bright **green**, and appeared contiguous with warmer and turbid green water **in** the bays and lagoons. Chlorophyll concentrations were apparently slightly higher than those offshore. In water deeper than **about** 10 m, a band of very cold (-0.5 to 0°C) and **clear** water was present. This band was 1-10 km wide and extended across **most** of the study area (141° to 143°W). Small scattered bits of ice were observed throughout this cold water, with a higher concentration of 1-25% brash ice along the thermal gradient separating it from warmer water **along** the shore.

Surface temperatures over the inner shelf between the 20 and 50 m **depth** contours were 1 to 2°C, with water as warm as 3°C at the northeast corner of the surveyed area (Fig. 23A) where the Mackenzie influence was largest. Turbidity **levels**, as inferred from the R640 Index (Fig. 23B), were also generally **low** over **the** inner shelf, equivalent to secchi depths of 6-13 m. Turbidity increased with distance from **shore** to maximum levels indicative of 4 m **secchi** depth at the shelf edge along the eastern side of the study area.



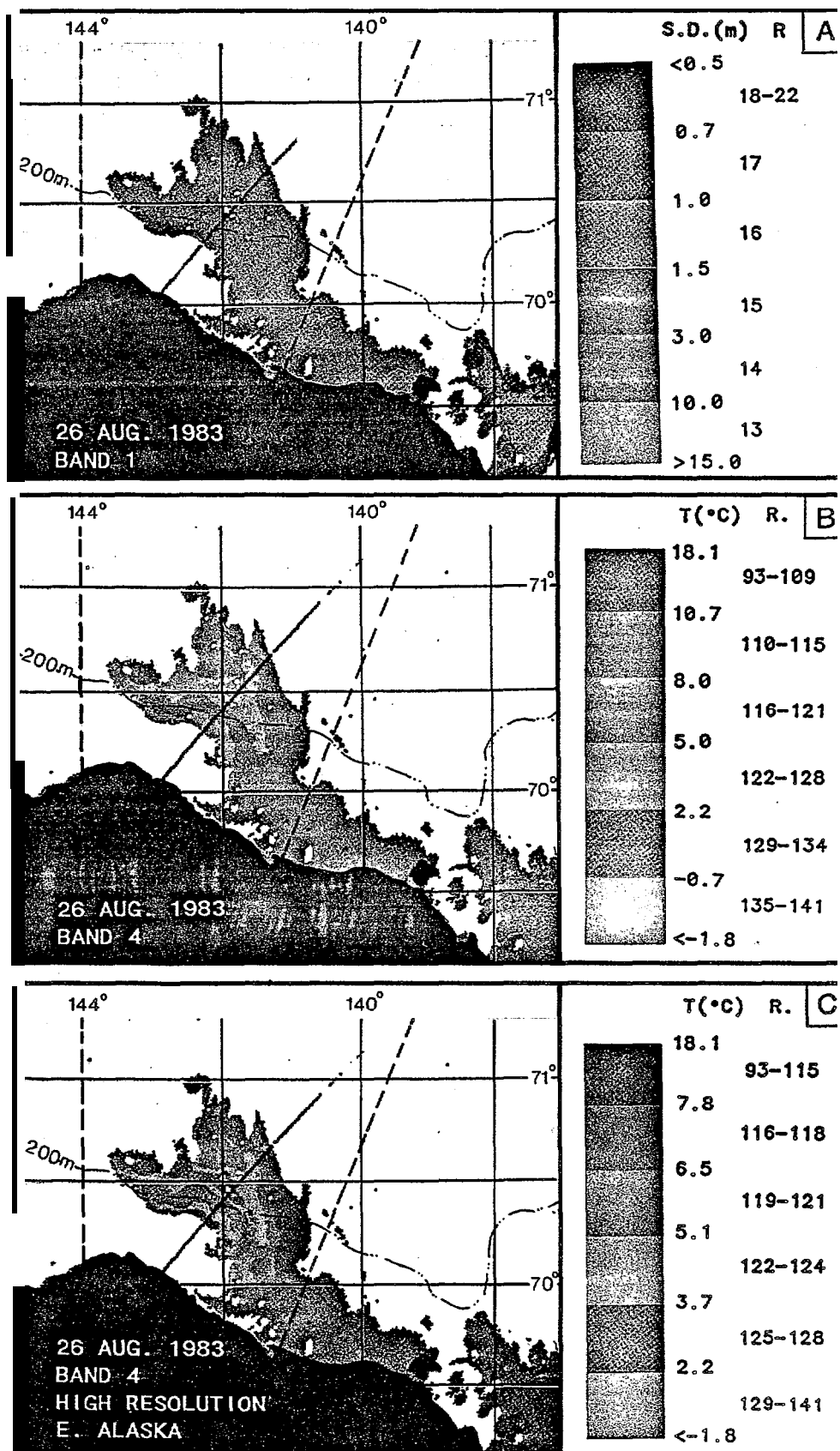


FIGURE 20. Satellite data for 26 August 1983 derived from the AVHRR sensor on the NOAA-7 satellite. A false color display is used to depict patterns of (A) surface reflectance - band 1, (B) surface temperature - band 4, and (C) surface temperature - band 4, reprocessed for high resolution within the official study area (outlined by dashed lines). For each color, the ranges of pixel radiance values, approximate secchi depths (A), and approximate temperatures (B, C) are shown.



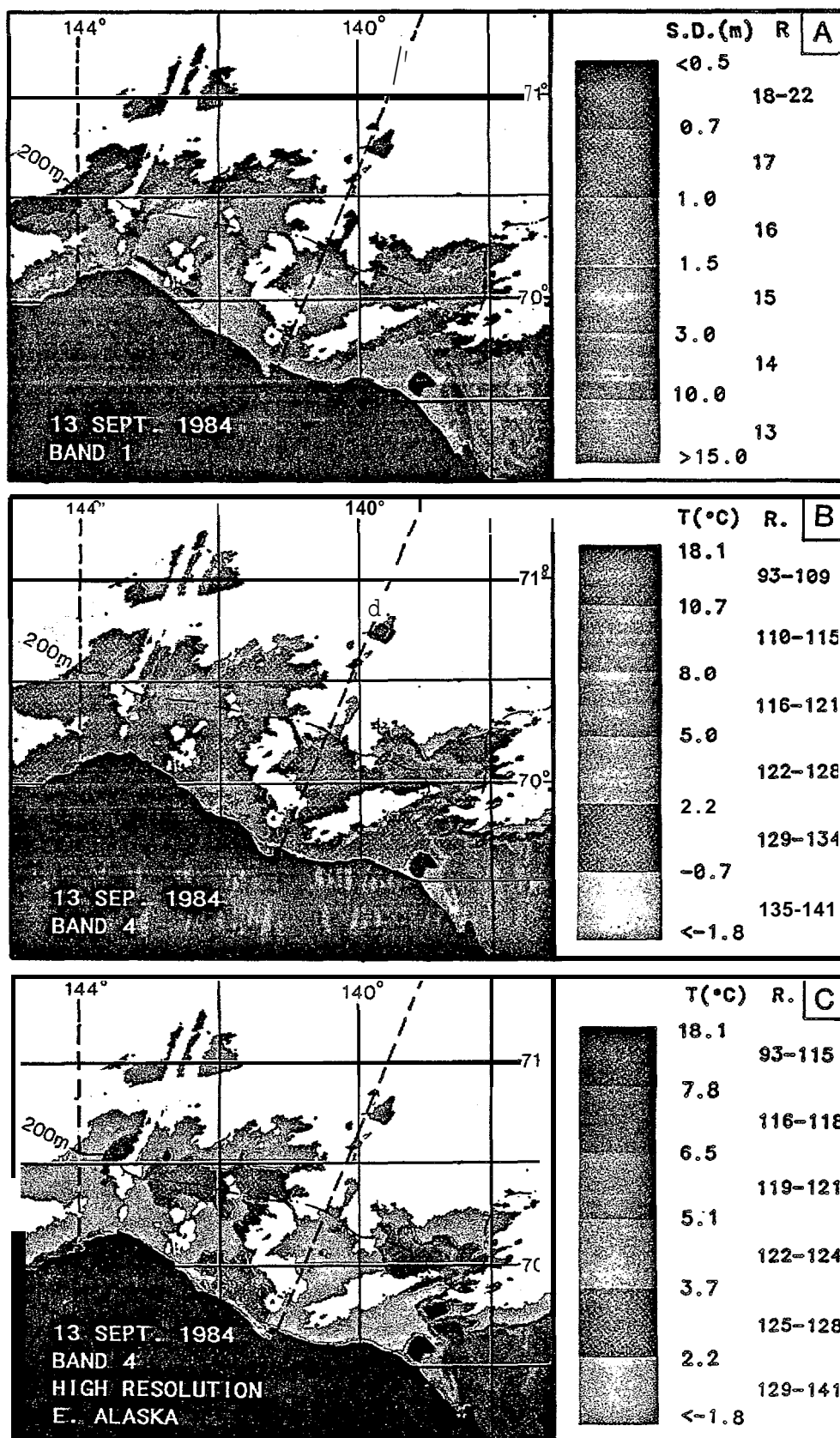


FIGURE 21. Satellite data for 13 September 1984 derived from the AVHRR sensor on the NOAA-8 satellite. A false color display is used to depict patterns of (A) surface reflectance - band 1, (B) surface temperature - band 4, and (C) surface temperature - band 4, reprocessed for high resolution within the official study area (outlined by dashed lines). For each color, the ranges of pixel radiance values, approximate secchi depths (A), and approximate temperatures (B, C) are Shorn



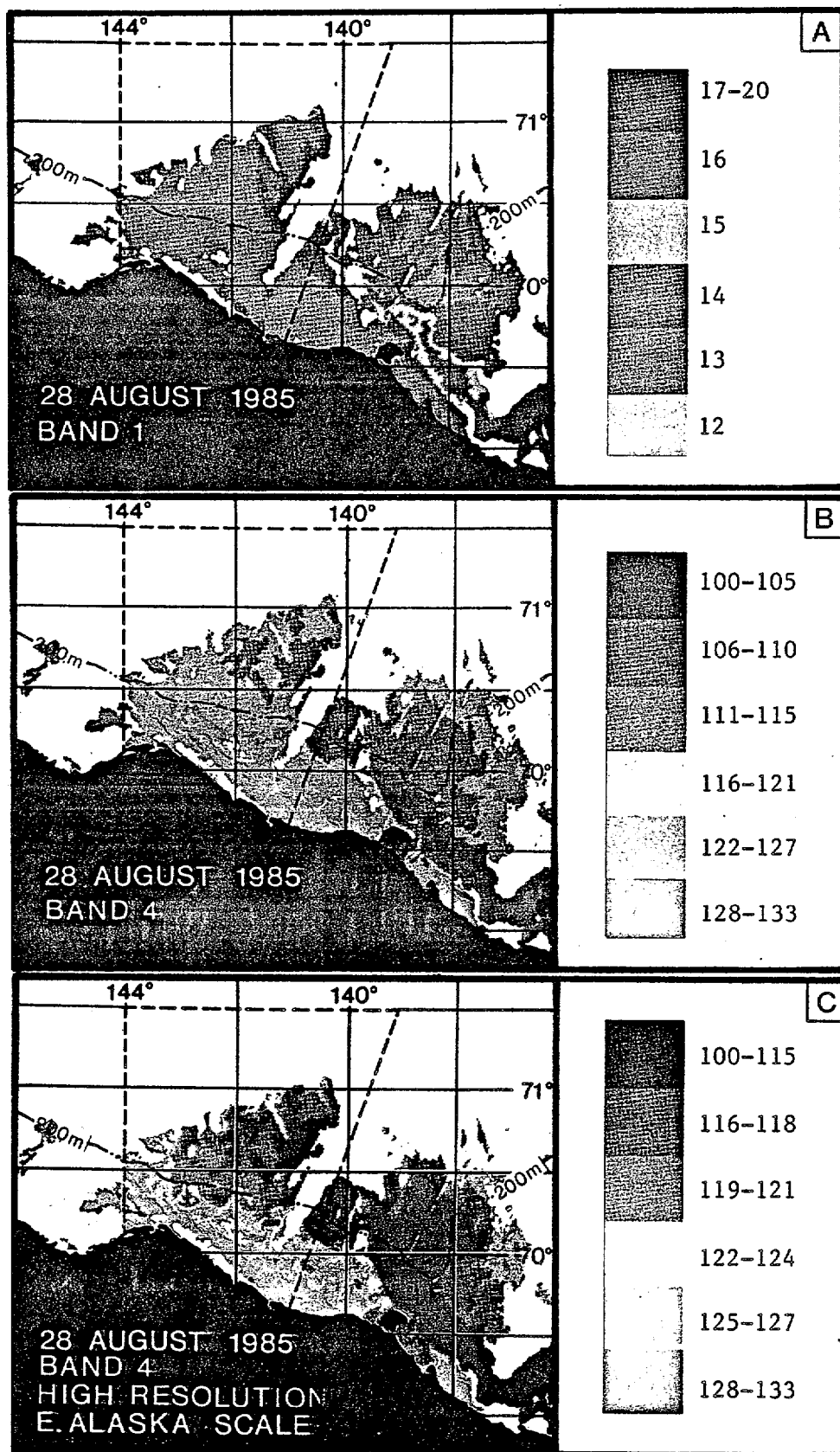


FIGURE 22. Satellite data for 28 August 1985 derived from the AVHRR sensor on the NOAA-9 satellite. A false color display is used to depict patterns of (A) surface reflectance - band 1, (B) surface temperature - band 4, and (C) surface temperature - band 4, reprocessed for high resolution within the official study area (outlined by dashed lines). Accompanying the images is the range of pixel radiance values for each color.



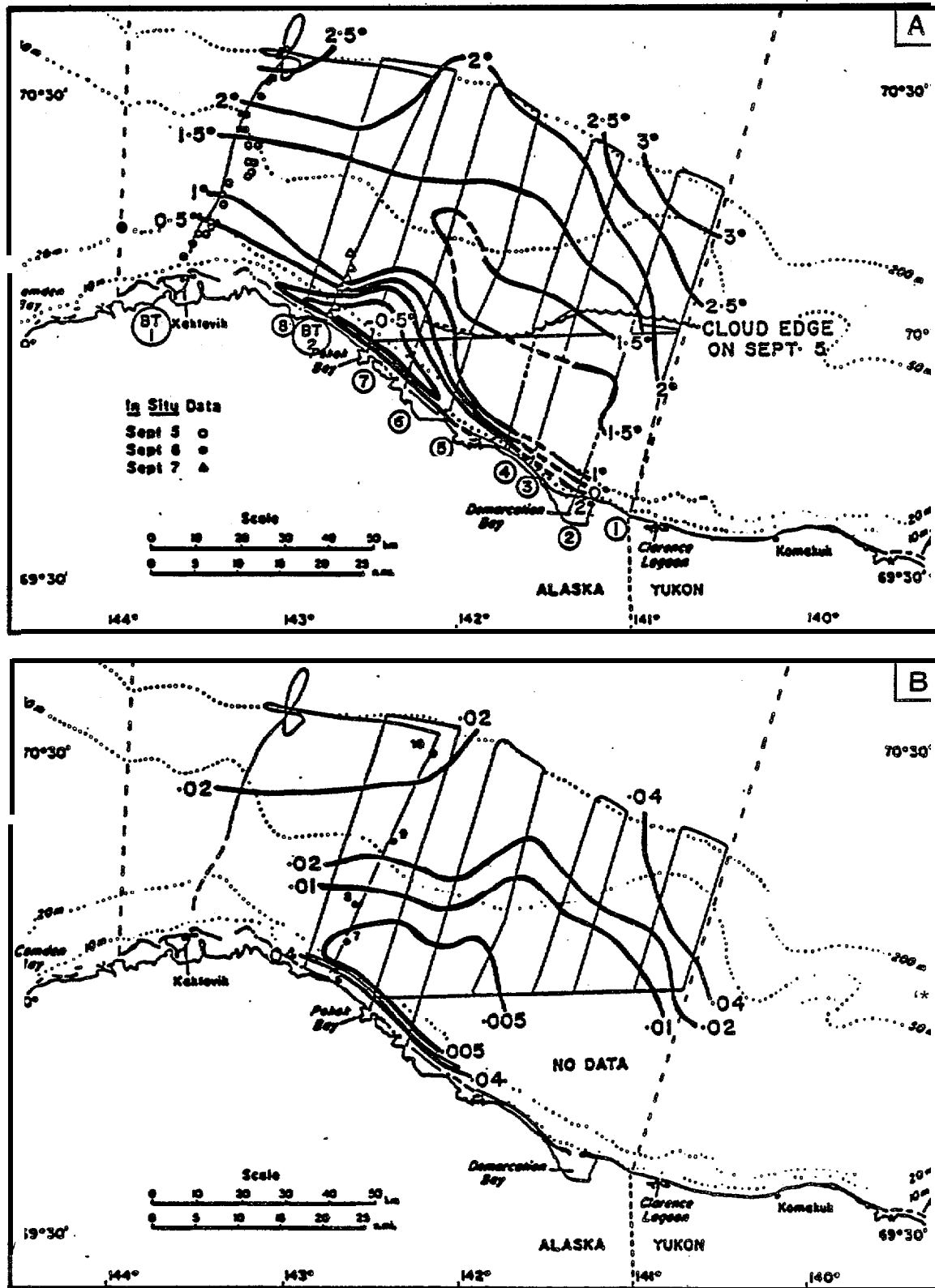


FIGURE 23. Distribution within the Eastern Alaskan Beaufort Sea on 5-6 September 1985 of (A) sea surface temperature ( $^{\circ}\text{C}$ ), as measured with the airborne radiation thermometer, and (B) the Red Reflectance Index R640 as measured with the 10S spectrometer. Symbols indicate locations of boat-based stations that provided in situ measurements for calibrations. The thinner lines are aircraft transects; circled numbers in (A) are transect numbers.

12-13 September 1985.--An aircraft survey of the study area was conducted on 12 September (continental **slope** area, 200-2000 m depths) and on 13 September (continental shelf, **0-200** m depths). No data were collected just north and east of Kaktovik because we were requested **to** avoid flying over whaling operations near **Kaktovik**. A **useable** satellite image was obtained for 13 September (Fig. 24).

As in **the** previous two weeks, comparatively **warm, turbid** water of Mackenzie Bay origin occurred over the continental slope and areas farther offshore along the eastern side of the study area. However, the core of the Mackenzie Bay water was now confined to an area between **142°W** and **138°W** (Fig. 24, 25), and was separated from the warmer waters within Mackenzie Bay **by** comparatively cooler temperatures off the Yukon coast.

Over the continental shelf, the surface oceanographic features measured from the aircraft on 5-6 September were **still** present on 12-13 September, but their positions had changed (Fig. 25, 26). The nearshore band of warm ( $>0.5^{\circ}\text{C}$ ), turbid water remained along much of the coastline out to about 3-4 km offshore. However, this feature was no longer present near Demarcation Bay, where it had been measured one week earlier. Very cold water ( $<-1.0^{\circ}\text{C}$ ) remained several kilometers north of **Pokok** Bay. Small widely scattered bits of ice were again observed throughout this cold water, but were more concentrated (0-20% brash) along its southern edge, on aircraft transects 5-7. (See Fig. 25 for transect numbers.)

Surface temperatures over the inner shelf had decreased from those measured one week earlier, with temperatures  $<0^{\circ}\text{C}$  extending to the 50 m isobath. There a large-scale thermal front separated shelf waters colder than about  $0^{\circ}\text{C}$  from water warmer than  $\pm 0.5^{\circ}\text{C}$  to the north. In the western **half** of **the** survey area, the front was visible from the aircraft as a change in surface roughness. The front was very intense along the easternmost transect, where temperature increased by  $3^{\circ}\text{C}$  over  $<4$  km. In many places along the easternmost transects, the front was associated with mist and 'sea-smoke'. The eastern half of the shelf (where surface temperatures were  $<0^{\circ}\text{C}$ ) was covered by extensive slicks visible from the aircraft. Most of these were not associated with a temperature or color change, but their orientation was consistent with the general SE-NW trend of the isotherms. An eddy 4 to 5 km in diameter was visible in a **slick** pattern near the south end of transect 2 off Demarcation Bay. The eddy was in an area of slightly warmer water; it may have represented the center of a large gyre. Additional evidence of this eddy is provided by the shape of the isotherms (Fig. 25), the absence of a warm band of water **along** the coast, and the ice piled up on the beach.

The surface waters in the western and central study area, the outer **half** of the continental shelf and farther offshore had intermediate temperatures ( $0.5$  to  $1.5^{\circ}\text{C}$ ). The area of intermediate-temperature surface water was much larger than one week earlier (5-6 September, Fig. 23A), **when the  $2.0^{\circ}\text{C}$  isotherm** was over the shelf edge (south of the 200 m contour) across **almost all** of the study **area**.

18 September 1985.--The presence of strong northwest winds on 15-18 September (Fig. 7) resulted in drastic changes in water mass distributions (compare Fig. 27 with Fig. 25 and 26). On 13 September the water had been



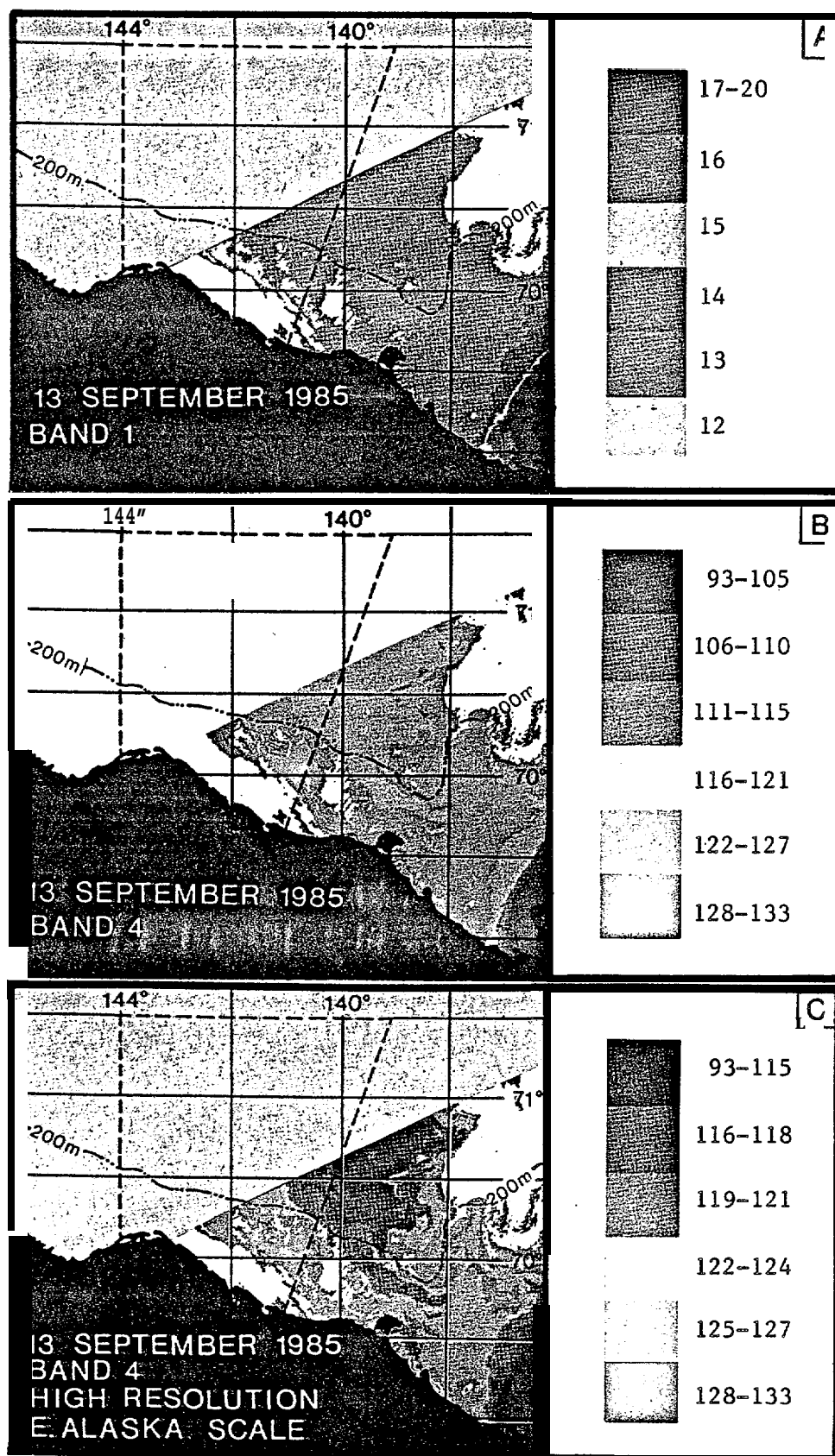


FIGURE 24. Satellite data for 13 September 1985 derived from the AVHRR sensor on the NOAA-9 satellite. A false color display is used to depict patterns of (A) surface reflectance - band 1, (B) surface temperature - band 4, and (C) surface temperature - band 4, reprocessed for high resolution within the official study area (outlined by dashed lines). Accompanying the images is the range of pixel radiance values for each color.

100

100

100

relatively **clear** (band 1 pixel level 13) **almost** everywhere outside eastern Mackenzie Bay. By 18 September, higher band 1 radiance levels were found in waters adjacent to essentially **all** ice and land boundaries. The increases were presumably due to the presence of large amounts of sub-resolution brash ice near the pack ice edge, and resuspended sediments near the shore. Both **would** be produced by the strong winds and the accompanying high sea states.

Surface temperatures within the official study area were reduced and more homogeneous than those on **13 September (pixel levels formerly 116-133; now 133-137)**. Nevertheless, remnants of warmer water were **still** present in the **eastern half** of the official study area, representing vestiges of the warm water observed there on 13 September. However, even the warmest water in Mackenzie Bay was **colder** (band 4 levels **119-121**) than the warmest Eastern Alaska water had been 5 days previously (**band 4 levels 116-118**). The reductions in surface temperature are consistent with a large amount of heat lost to the atmosphere and to vertical mixing. The CTD profile data provide further supporting evidence for these sources of heat loss (see p. 88-91). **Advection** of cold water from far offshore probably played a minor role in the cooling process because of the great **distances** involved and the relatively short (3 day) period of strong winds preceding **18 September**.

22 September 1985. --Despite the presence of cloud and ice over the entire Eastern Alaska study region, this pair of images (Fig. 28) documented the further modification of surface conditions in adjacent Canadian waters after an additional 4 days of W-NW winds. Compared to **18 September**, there was a **slight** reduction in band 1 radiance levels "adjacent to shoreline areas, possibly because the slightly **lower** wind speed reduced the levels of sediment resuspension. The thermal (band 4) data, on the other hand, revealed a continuing decrease in temperature. By 22 September the warmest waters found in Mackenzie Bay had pixel levels of 125-130, reduced from levels of **119-121** on 18 September (**cf. Fig. 27**), and indicative of a temperature reduction of approximately 4 C°.

By late September of 1985, Mackenzie Bay water was no **longer** exerting an **important** influence on surface oceanographic conditions of the Eastern Alaskan study area. This situation probably persisted into October, as the weak to moderate easterly winds of 26-28 September (Fig. 7 on p. 21) **likely** were insufficient to advect Mackenzie Bay water as far west as the Eastern Alaskan Beaufort Sea. Moreover, water in Mackenzie Bay **itself** was **considerably** colder in late September than earlier, presumably because of the **large** degree of vertical mixing and surface heat **loss**, and reduction in both the heat content and volume discharges of the Mackenzie River itself.

26 August 1986. --During the week before the 1986 field-study began, **cloud** cover persisted throughout virtually **all** of the study area. A major **low** pressure **system** had passed through **the** study area on **21-23 August**, with strong **northwest** winds. The best satellite data for this period, from **26 August 1986**, were digitally processed but are not shown here because they were limited to **the** eastern boundary of the study area and regions off the Yukon coast north to **70°20'N**. Along the eastern boundary, a broad band of warm water (**>3-4°C**) was present over the outer continental **shelf** and slope. Very cold surface temperatures were observed over the remainder of the shelf and over **abyssal** depths farther offshore. The much warmer water (**>7°C**) of the

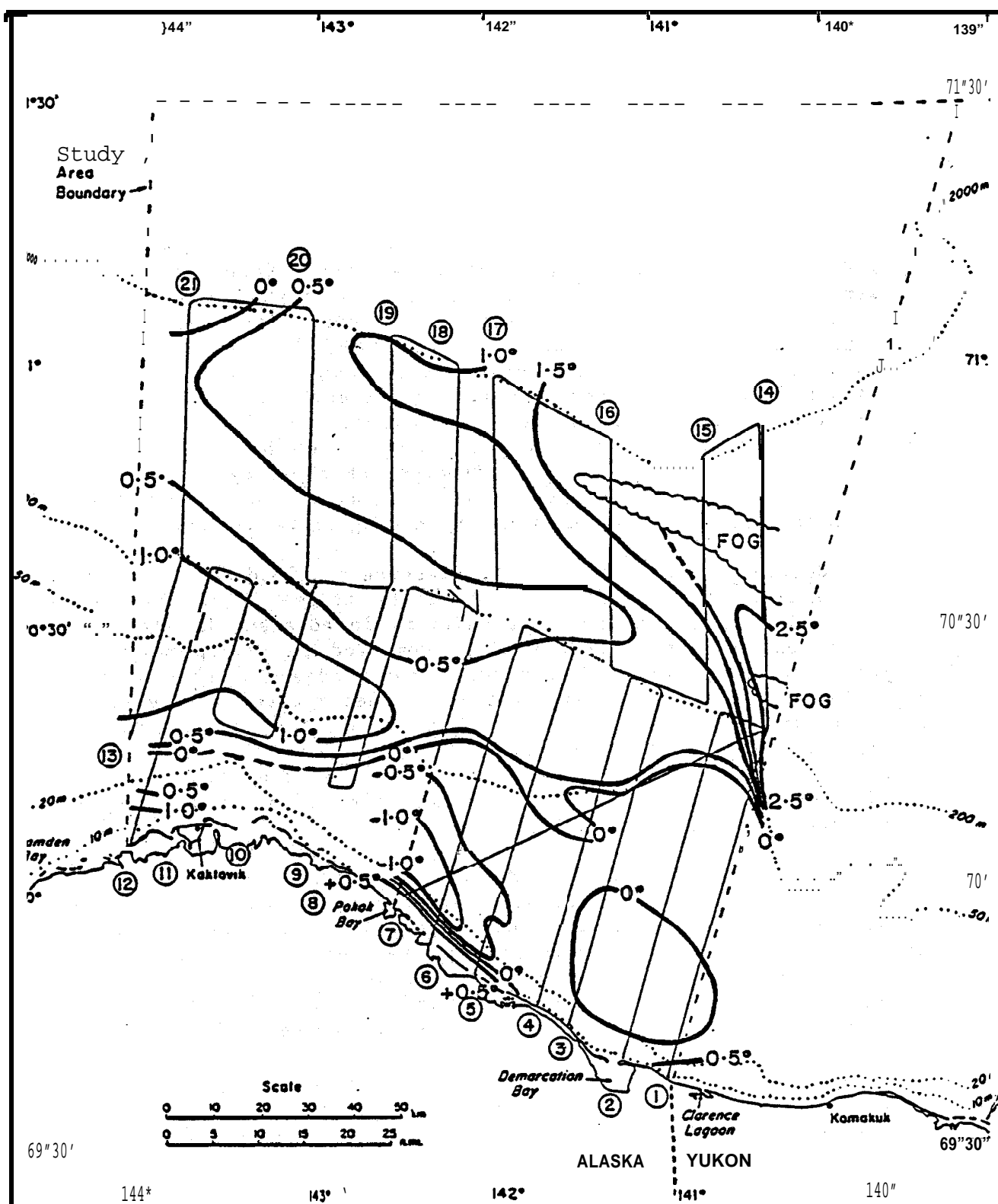


FIGURE 25. Distribution of sea surface temperature ( $^{\circ}\text{C}$ ) in the Eastern Alaskan Beaufort Sea on 12-13 September 1985, as measured with an airborne radiation thermometer. The thinner lines are the aircraft transects; circled numbers are transect numbers.

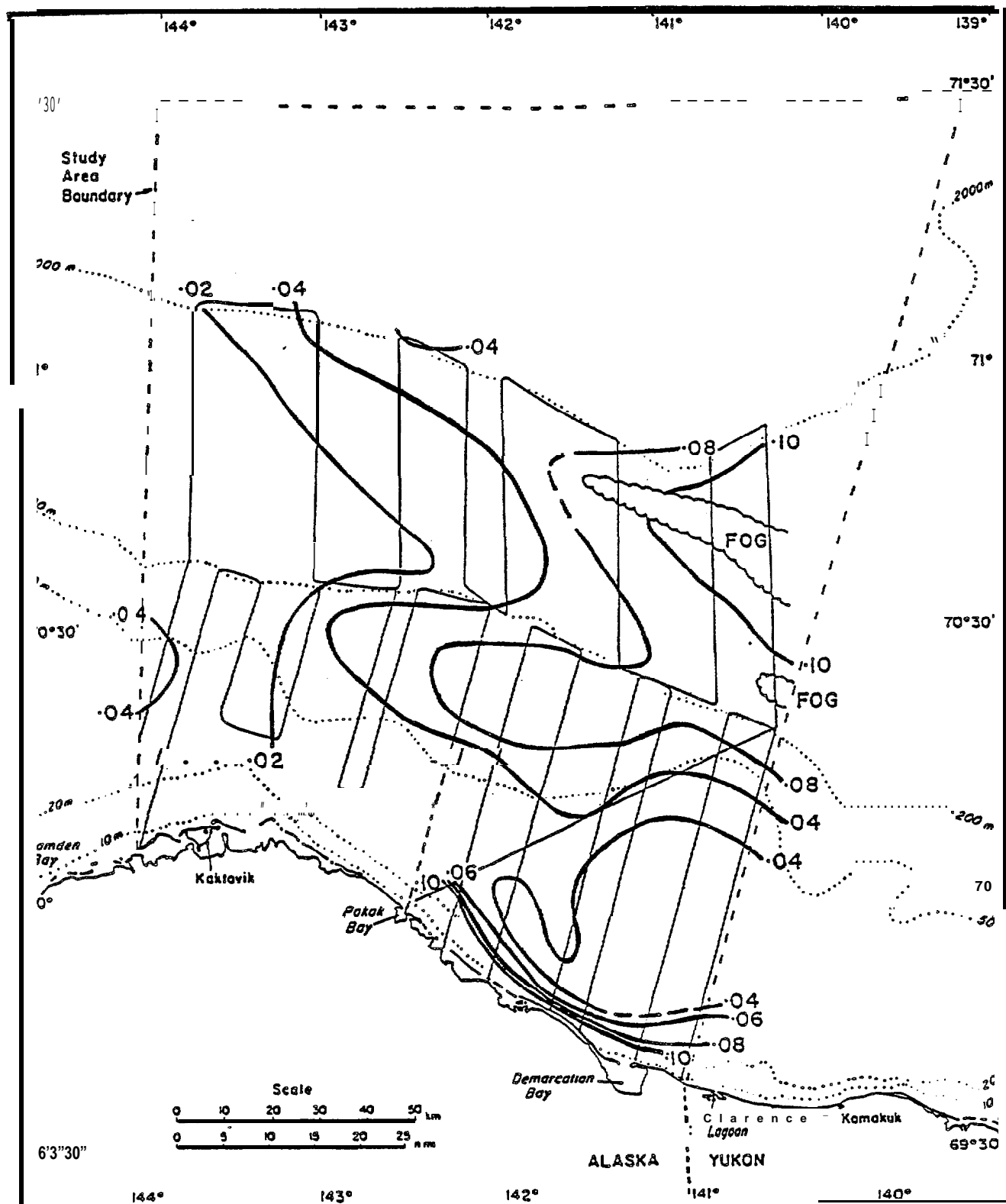


FIGURE 26. Distribution of the Red Reflectance Index R640 in the Eastern Alaskan Beaufort Sea on 12-13 September 1985, as measured with the IOS spectrometer. R640 increases with increasing turbidity of the upper water column. The thinner lines are the aircraft transects.

Mackenzie River **plume** was confined to within 20-30 km of **the Mackenzie Delta**, presumably as a result of the strong northwest winds of the preceding few days.

4-6 September 1986. --Aircraft measurements were obtained over the continental shelf on 4-5 September (Fig. 29, 30), including additional flight lines west of Herschel Island (Fig. 31). On 6-7 September, aircraft surveys were conducted in offshore areas and to the east of Herschel Island. Good satellite data were obtained on 6 September (Fig. 32, 33A).

With the **exception** of the nearshore zones from **Pokok Bay** to Demarcation Bay (discussed below), surface conditions were fairly uniform throughout, the **study** area. Temperatures ranged from 2 to **3°C**, and turbidity levels were very **low** (>10 m secchi depth in most areas). The core of the warmer, more turbid water of Mackenzie Bay origin remained east of the study area. It followed the edge **of** the Yukon continental shelf northwestward, but then turned north at approximately **139°30'W** (Fig. 32). However, the influence of warm Mackenzie Bay water did extend into the study area in two distinct areas:

- Far offshore, well beyond the shelf break along the eastern boundary o'f the study area, and
- As a coastal band, 20 km in width, extending west past Herschel Island and into the study area (discussed in 'Inshore Fine-Scale Oceanographic Features', p. 102 **ff**).

The west half of the study area had somewhat reduced surface temperatures (**<2.5°C**) and turbidities (>10 m secchi depth), possibly associated with the scattered ice pans present in this area. However, sea surface temperatures exceeded those of the previous year (**cf.** Fig. 23) by 1-2 Co, particularly over the inner and middle portion of the continental shelf.

8 September 1986. --The satellite data for this date provided coverage of the continental **shelf** proper. The visible band data (not shown) indicated **that** turbidity levels in the study area were low, viz >2.5-10 m **secchi** depths. Enhanced levels of turbidity were confined **to narrow** intermittent bands within a few kilometers of the coast.

Warm surface waters occurred far offshore **along the** eastern edge of the study area, and over the eastern half of **the** continental shelf (Fig. 33B). East of the study area, warmer Mackenzie Bay water (**>5°C**) was found. However, this warm core had been displaced approximately 10 km eastwards since 6 September. Surface temperatures over the inner **shelf** part of our study area were also reduced, especially between **141°W** and Herschel Island where temperatures within 20 km of shore had decreased from over 3.7 to below **2.2°C**. In the western portion of the study area, the cold waters (**<2.2°C**) had expanded in area.

10-11 September 1986. --Satellite "measurements were obtained over most of the study area on **10 September** (Fig. 33C). A corrective offset of **-13 bits** was applied to all band 4 data, as described in 'Methods' on p. 38. On 11 September, aircraft-based measurements were collected over the continental shelf within the study area (Fig. 34, 35).

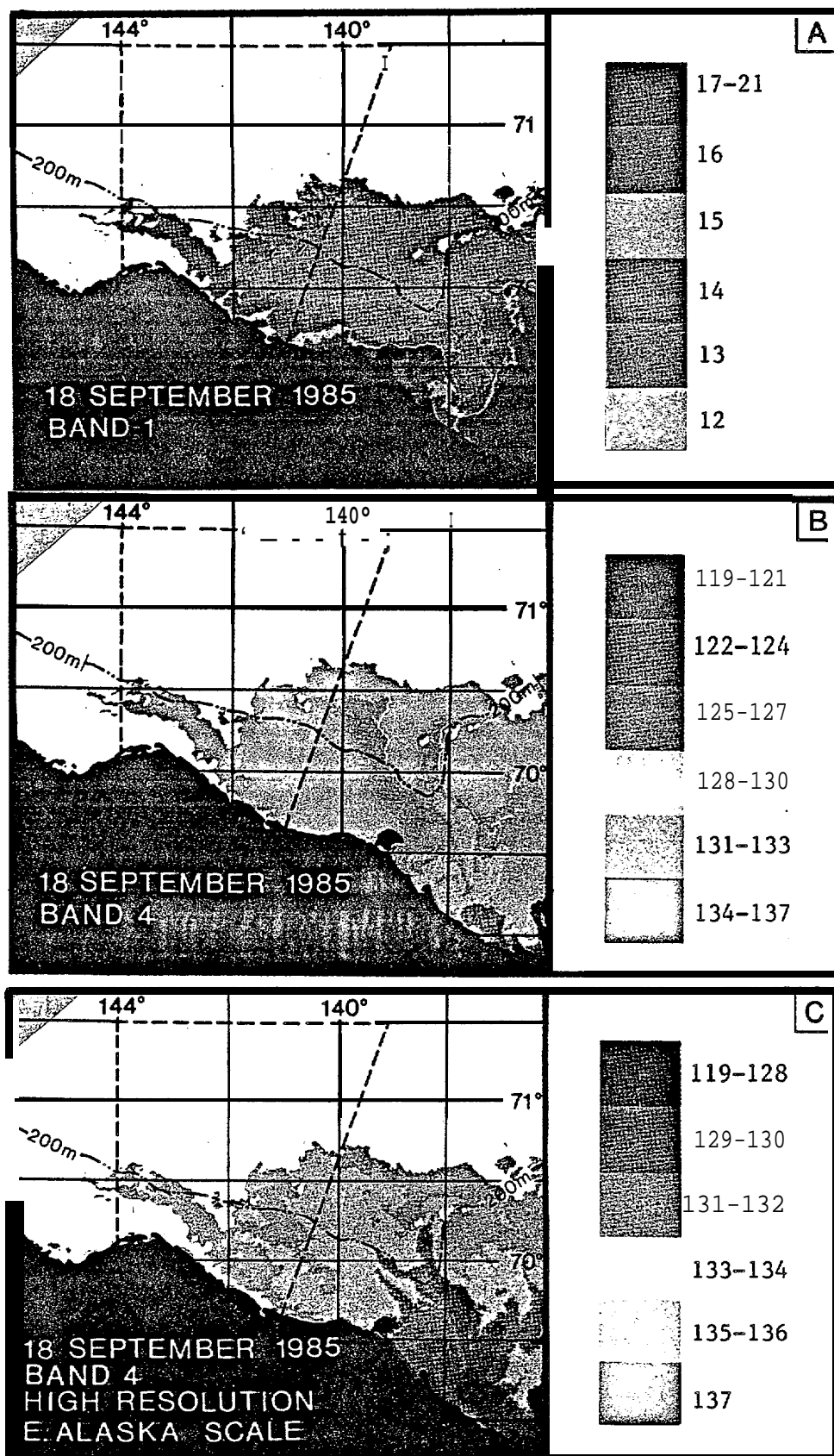


FIGURE 27. Satellite data for 18 September 1985 derived from the AVHRR sensor on the NOAA-9 satellite. A false color display is used to depict patterns of (A) surface reflectance - band 1, (B) surface temperature - band 4, and (C) surface temperature - band 4, reprocessed for high resolution within the official study area (out lined by dashed lines). Accompanying the images is the range of pixel radiance values for each color.





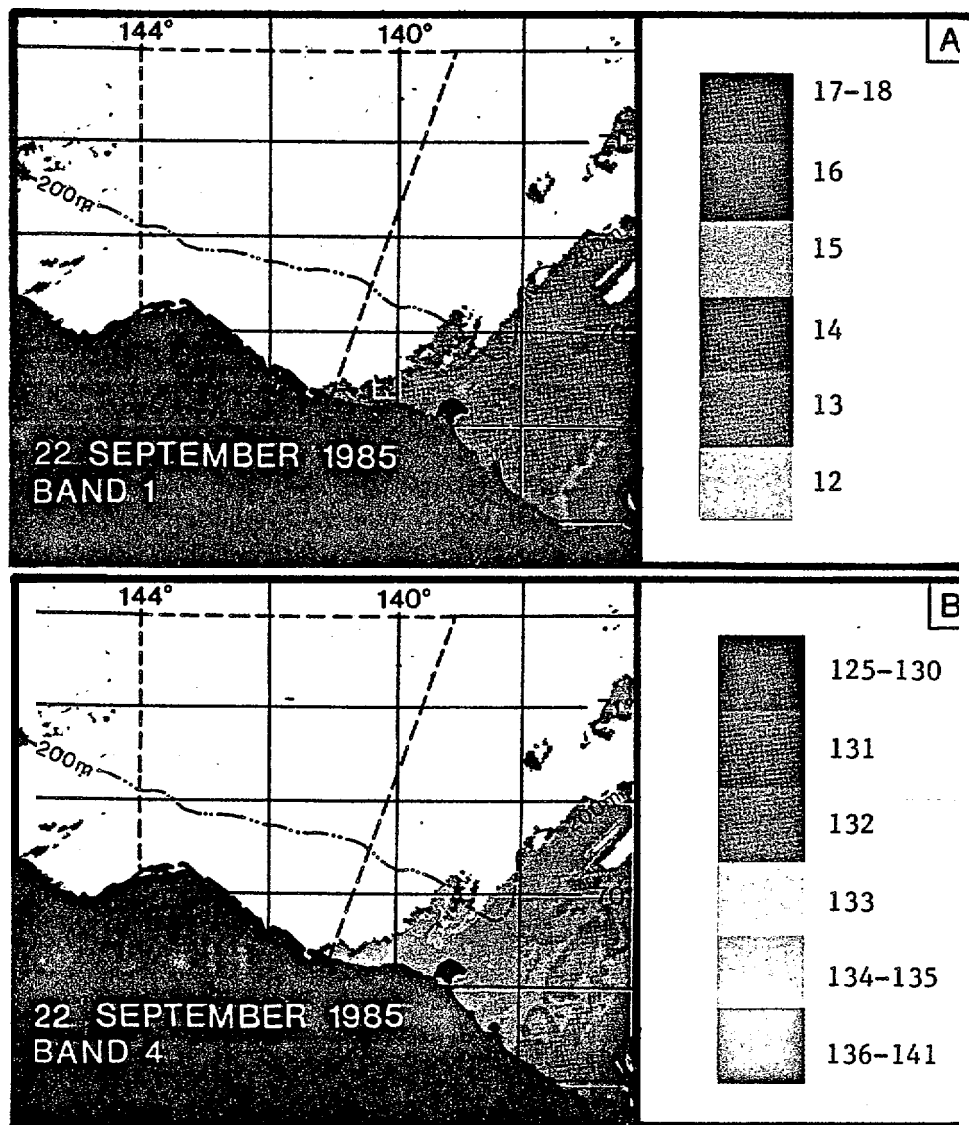


FIGURE 28. Satellite imagery for 22 September 1985 derived from the AVHRR sensor on the NOAA-9 satellite. (A) Surface reflectance - band 1. (B) Surface temperature - band 4. The study area is outlined by dashed lines. Accompanying the images is the range of pixel radiance values for each color.

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The study area was characterized by increasing surface temperature from west to east. This appeared to be due to cooling in the west and increased influence of Mackenzie Bay water in the east. Throughout the western half of the study area temperatures were sharply reduced from the previous week. Temperatures were generally below  $1.0^{\circ}\text{C}$ , and  $-0.5^{\circ}\text{C}$  along the western-boundary (Fig. 34). From about  $142.5^{\circ}\text{W}$  to the eastern boundary of the study area, temperatures increased to  $2.5^{\circ}\text{C}$  or more. A fairly intense thermal front extended north from the coast to the 2000 m isobath. A prominent temperature and turbidity maximum extended northwest from the coast near Demarcation Bay on both 10 and 11 September (see 'Inshore Fine-Scale Oceanographic Features', below).

From the eastern boundary to Herschel Island, the extensive area of relatively low temperatures observed over the continental shelf on 8 September ( $<2.8^{\circ}\text{C}$ ) had been replaced by warmer surface temperatures (approx.  $3.5^{\circ}\text{C}$ ). This warming was most pronounced to the north and west of Herschel Island, where temperatures of  $3.7$ - $5.1^{\circ}\text{C}$  or more were present on 10 September, approximately 0.5 to  $1.5^{\circ}\text{C}$  greater than two days earlier. Farther offshore in this same sector, the extension of the Mackenzie Bay water (temperatures  $>5.1^{\circ}\text{C}$ ) followed the shelf edge west to  $140^{\circ}\text{W}$  before branching north. As on 6 and 8 September, broad filaments from this Mackenzie Bay water (temperatures  $>3.7^{\circ}\text{C}$ ) were observed within the northeast corner of the study area.

14-15 September, 1986. --Most of the study area was visible in the satellite data obtained on 14 September (Fig. 36). A correction for atmospheric effects in the band 4 (thermal) data was required, similar to that used for the 10 September satellite data. Aircraft-based measurements (Fig. 34) were made on 14-15 September far offshore beyond the continental shelf and in the inshore region from Komakuk to Clarence Lagoon. Further reductions in surface temperatures were evident in these data. However, warm water ( $2.5$ - $3.5^{\circ}\text{C}$ ) of Mackenzie Bay origin continued to impinge on the eastern half of the study area. Elsewhere in the study area, temperatures were much cooler ( $<2.2^{\circ}\text{C}$ ), with values as low as  $-0.5^{\circ}\text{C}$  near the western boundary.

North of Komakuk along the Yukon coast, at least two discrete bands of turbid, relatively warm (up to  $4^{\circ}\text{C}$ ) water extended up to 20-30 km offshore. Aircraft-based visual observations indicated that the surface layer within 5-10 km of the coast was being advected west. This was consistent with the weak to moderate easterly winds on 14 September (Fig. 8).

26 September 1986---The satellite data of 26 September 1986 (Fig. 37) were obtained after the boat and airborne remote sensing programs ended, and after two intense northwesterly wind events from 21 to 25 September. Throughout the study area, surface temperatures were considerably lower than on 14 September and earlier. Calibration data are lacking, but estimated temperatures were  $<1^{\circ}\text{C}$  throughout the study area based on the calibration of previous satellite imagery. Unlike temperatures, turbidities within 10-15 km of the coast had increased. This likely was the result of wave-induced resuspension of nearshore sediments during the intense storms of the preceding five days.

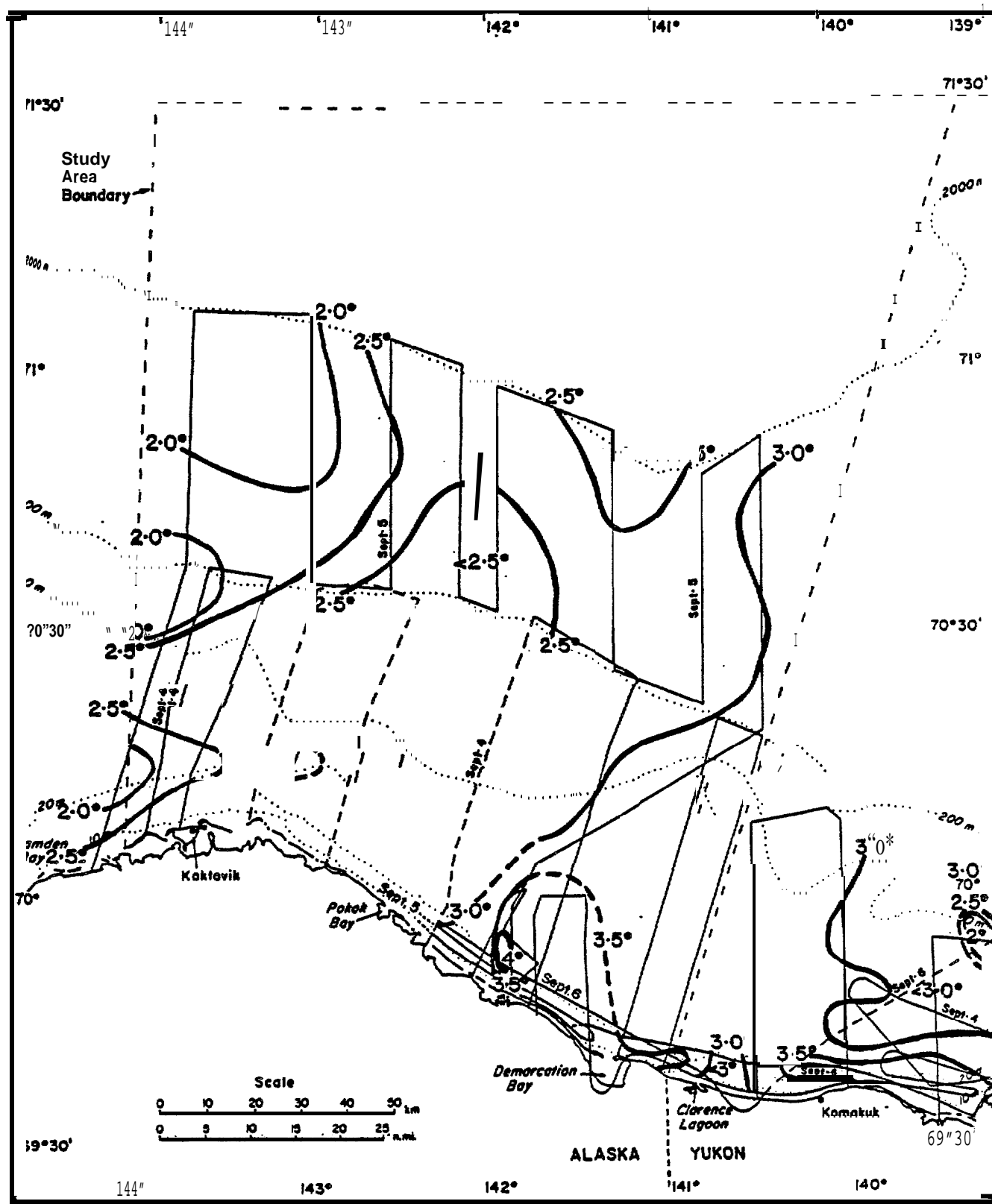


FIGURE 29. Distribution of sea surface temperature ( $^{\circ}\text{C}$ ) in the Eastern Alaskan Beaufort Sea on 4-6 September 1986, as measured with an airborne radiation thermometer. The thinner lines are the aircraft transects.

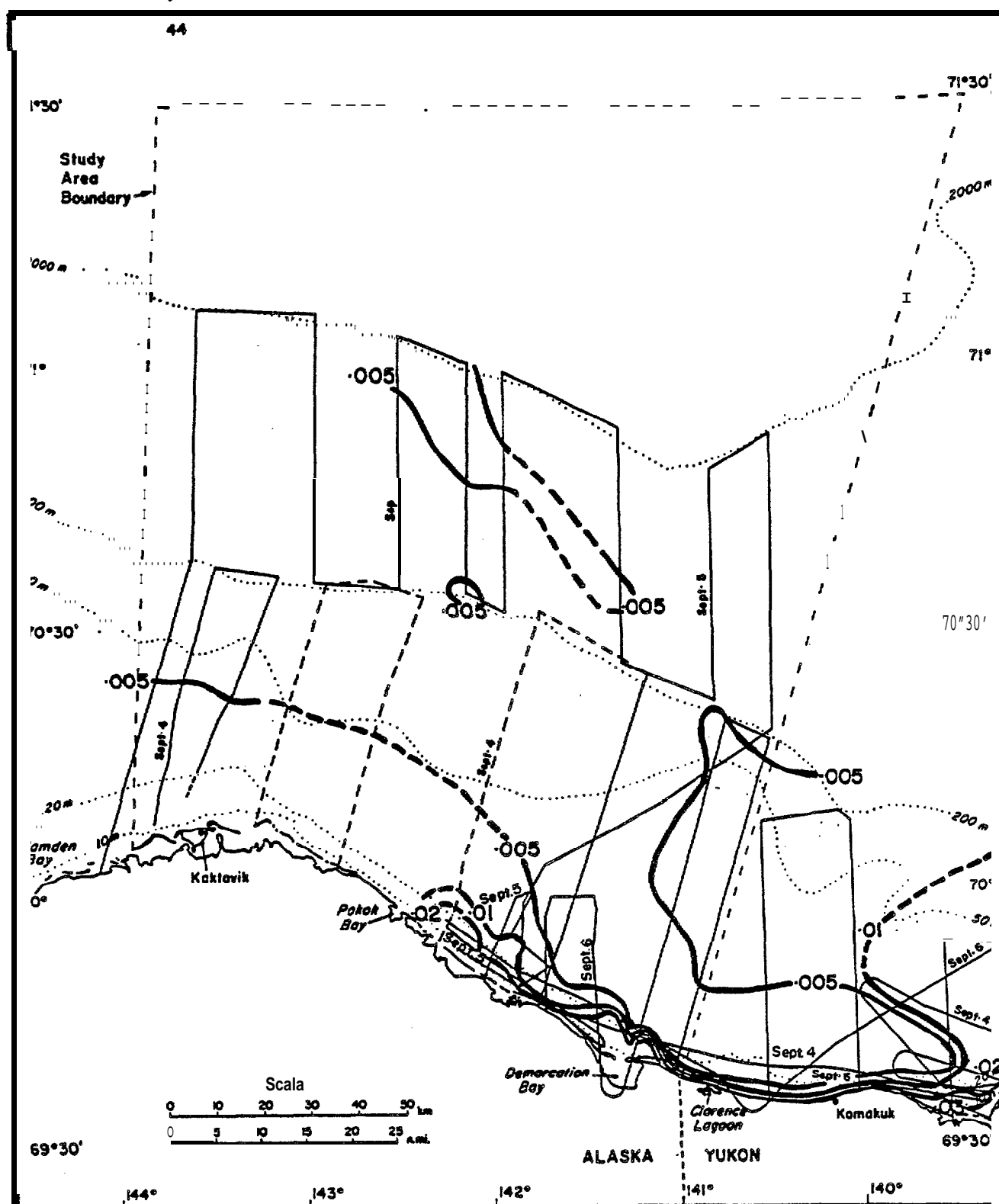


FIGURE 30. Distribution of the Red Reflectance Index R640 in the Eastern Alaskan Beaufort Sea on 4-6 September 1986, as measured with the 10S spectrometer. R640 increases with increasing turbidity of the upper water column. The thinner lines are the aircraft transects.

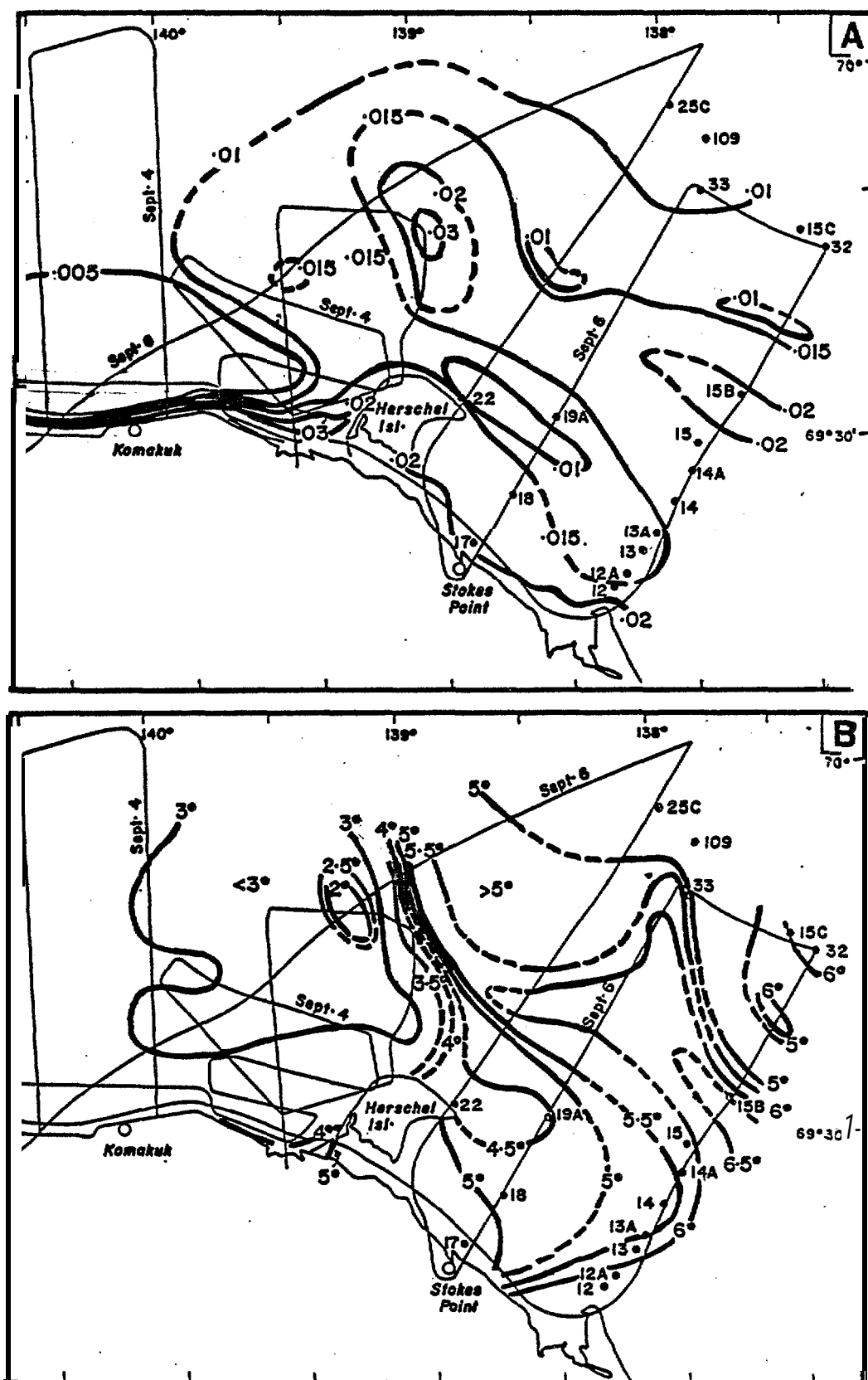
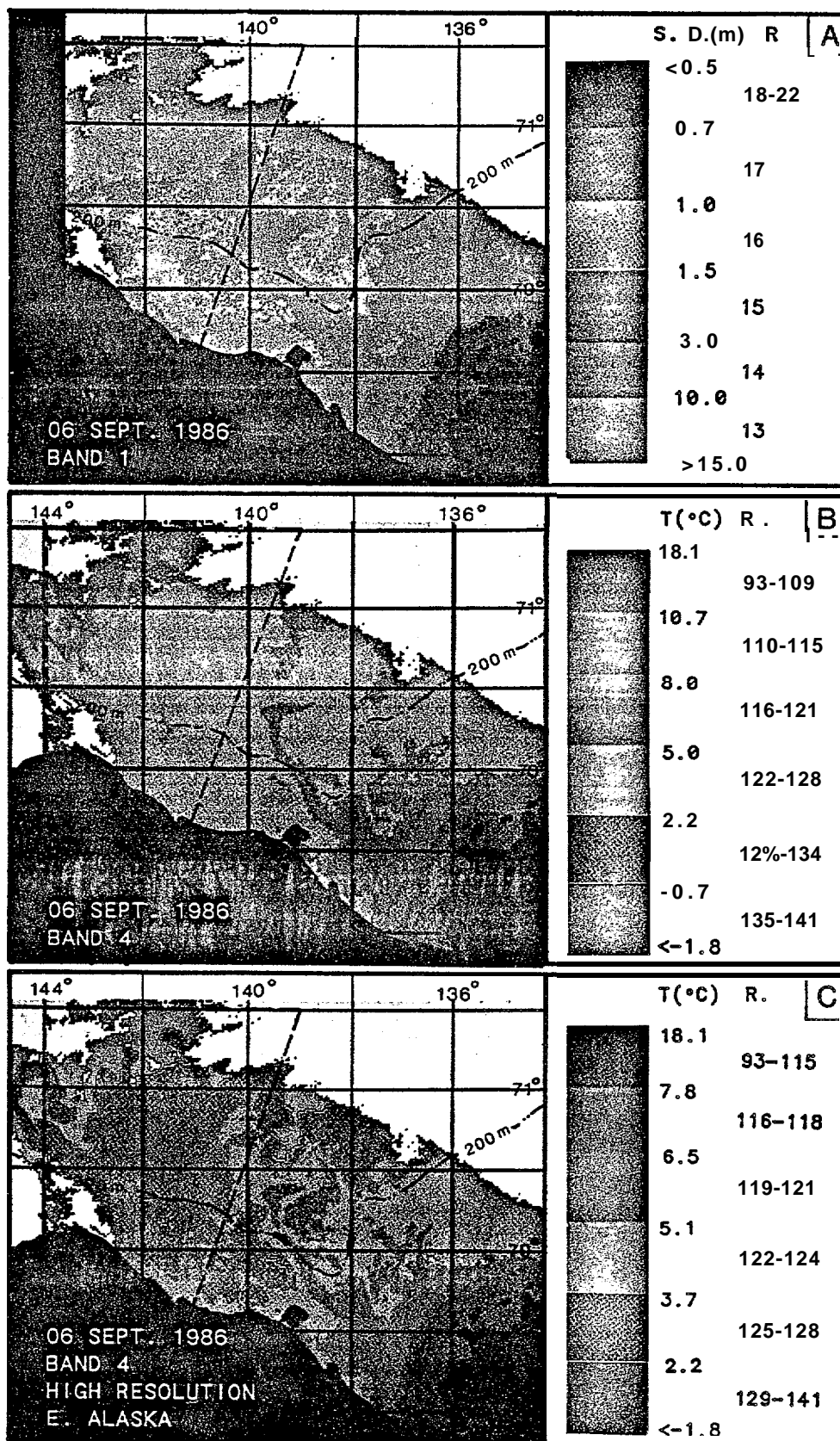


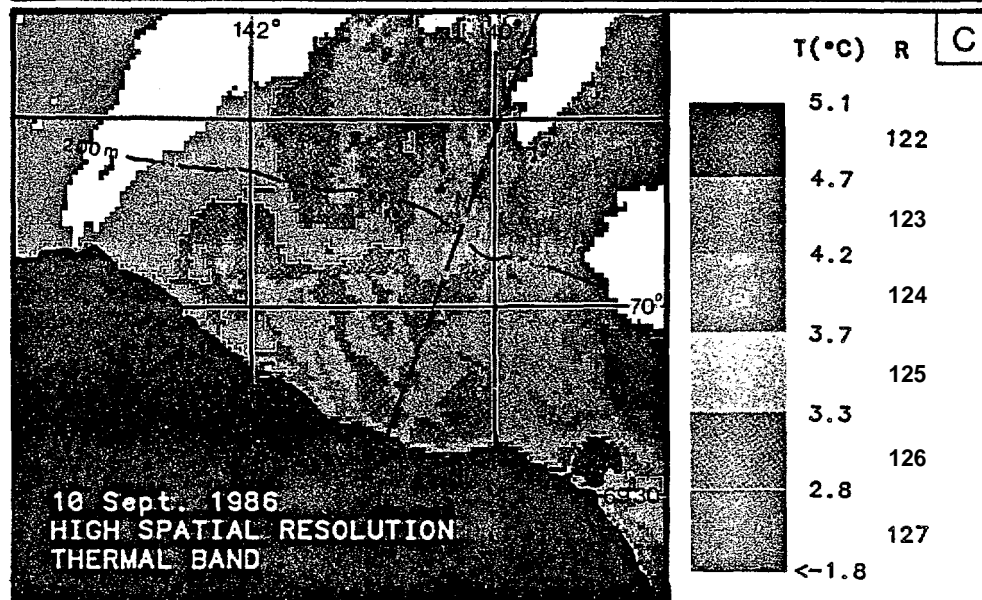
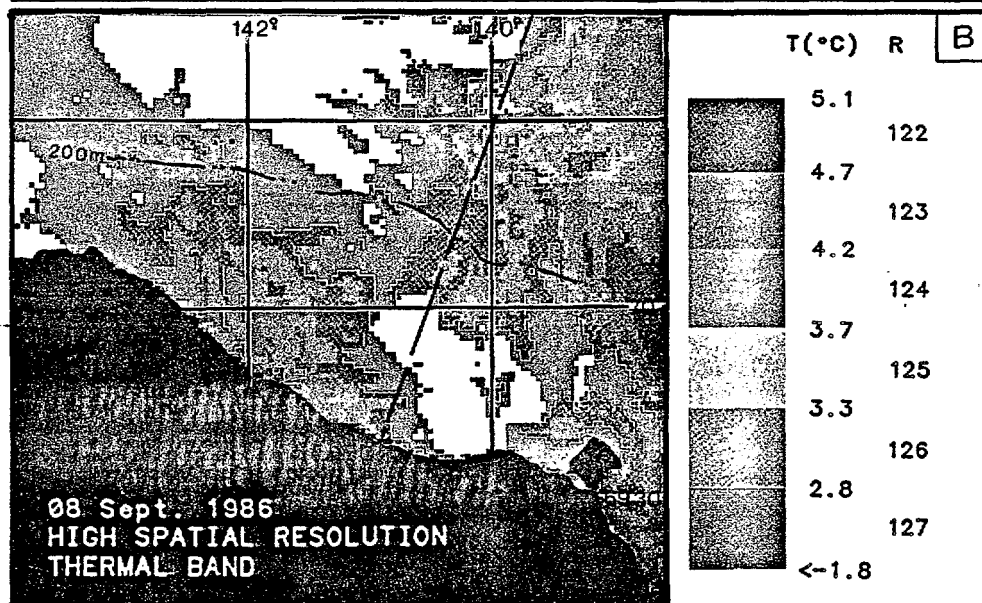
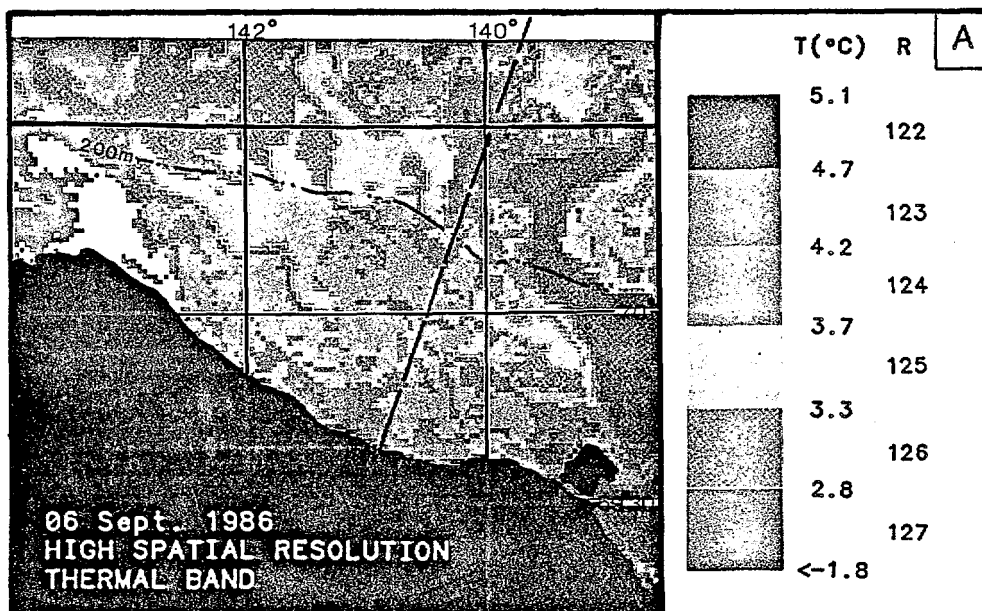
FIGURE 31. Distribution of (A) Red Reflectance Index R640 and (B) surface temperature, as measured with aircraft sensors on 4-6 September 1986 near Herschel Island. The thinner lines are the aircraft transects.



**FIGURE 32.** Satellite data for 6 September 1986 derived from the AVHRR sensor on the NOAA-9 satellite. A false color display is used to depict patterns of (A) surface reflectance - band 1, (B) surface temperature - band 4, and (C) surface temperature - band 4, reprocessed for high resolution within the official study area (outlined by dashed lines). Accompanying the images is the range of pixel radiance values (R), and their corresponding secchi depth (S.D. ) and temperature (T, °C) ranges, for each color.

FIGURE 33. Band 4 satellite data for the continental shelf and slope portions of the official study area for (A) 6 September, (B) 8 September and (C) 10 September 1986. The pixel ranges have been chosen to provide very high resolution of the smaller scale variations in temperature over the shelf. The eastern edge of the official study area is indicated by the dashed line. For each color, the range of pixel radiance values (R) and the corresponding temperature (T, °C) range are shown.





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Sharply reduced surface temperatures were apparent in Mackenzie Bay. Even in areas directly adjacent to the Mackenzie Delta, surface temperatures appeared to be no greater than 4°C. Turbidity levels, in contrast, were very high near the Delta, and also enhanced along the Yukon coast. This was again likely due to wave rather than riverine processes.

Summary of Broad-Scale Surface Distributions,--The surface distributions of temperature and turbidity in the Eastern Alaskan Beaufort Sea were mapped using **satellite** data (1983-1986) and aircraft data (1985-1986). Surface water properties in the Eastern Alaskan **study** area generally represent a transition between the warm, more turbid surface waters found to the east in Mackenzie Bay and the colder, clear Arctic Surface Waters found to the west. In the western portion of the study area, the Arctic Water characteristics are a **result** of the close proximity of the pack ice edge through the summer months, combined with the absence of major river discharges comparable to those of the Mackenzie River. Local estuarine discharges within the study area, particularly from the **Kongakut** River, may influence water properties, but the effects of these discharges are limited to small areas within several kilometers of the estuaries.

The warmer, more turbid water of Mackenzie Bay is advected northwest off the Yukon coast, with the core of this water type occurring as a comparatively narrow band over the shelf edge northeast of Herschel Island. North of Herschel Island, it often turns northward, resulting in a broad area of warmer water over depths exceeding 200 m along the eastern edge of the study area. Filaments of this warmer water were often observed within the eastern side of the study area, at considerable distances from shore. In late August of 1985, following easterly winds of unusually long duration and heavy ice conditions in the extreme eastern Canadian Beaufort Sea, the warm Mackenzie Bay water extended farther west than normal. This resulted in warmer-than-usual temperatures over the outer continental shelf and areas farther offshore. By mid-September of 1985 and 1986, northwest winds drove the Mackenzie Bay water east away from the study area. It was replaced by cold clear Arctic water, often containing ice floes from the offshore pack ice. In summers dominated by west and northwest winds (e.g. 1981 and 1982), such conditions are likely to occur earlier in the year, due to a much diminished influence of Mackenzie Bay water within the study area.

Over the continental shelf portion of the study area, surface waters are highly variable. Mackenzie Bay water commonly influences the eastern and offshore portions of the study area as discussed above. In addition, during 1986 Mackenzie Bay water appeared to penetrate into nearshore portions of the study area as a band approximately 20 km wide, advected past Herschel Island and into the study area along the coast. The warm water from Mackenzie Bay, combined with possible local estuarine discharges and greater solar insolation due to earlier ice clearing in August, resulted in warmer surface temperatures over the southeast part of the study area in 1986 than in 1985. In 1985, very cold and clear water was present over the inner and mid-shelf regions throughout the observational period, with slightly warmer temperatures being confined to a nearshore band within a few kilometers of the coast.

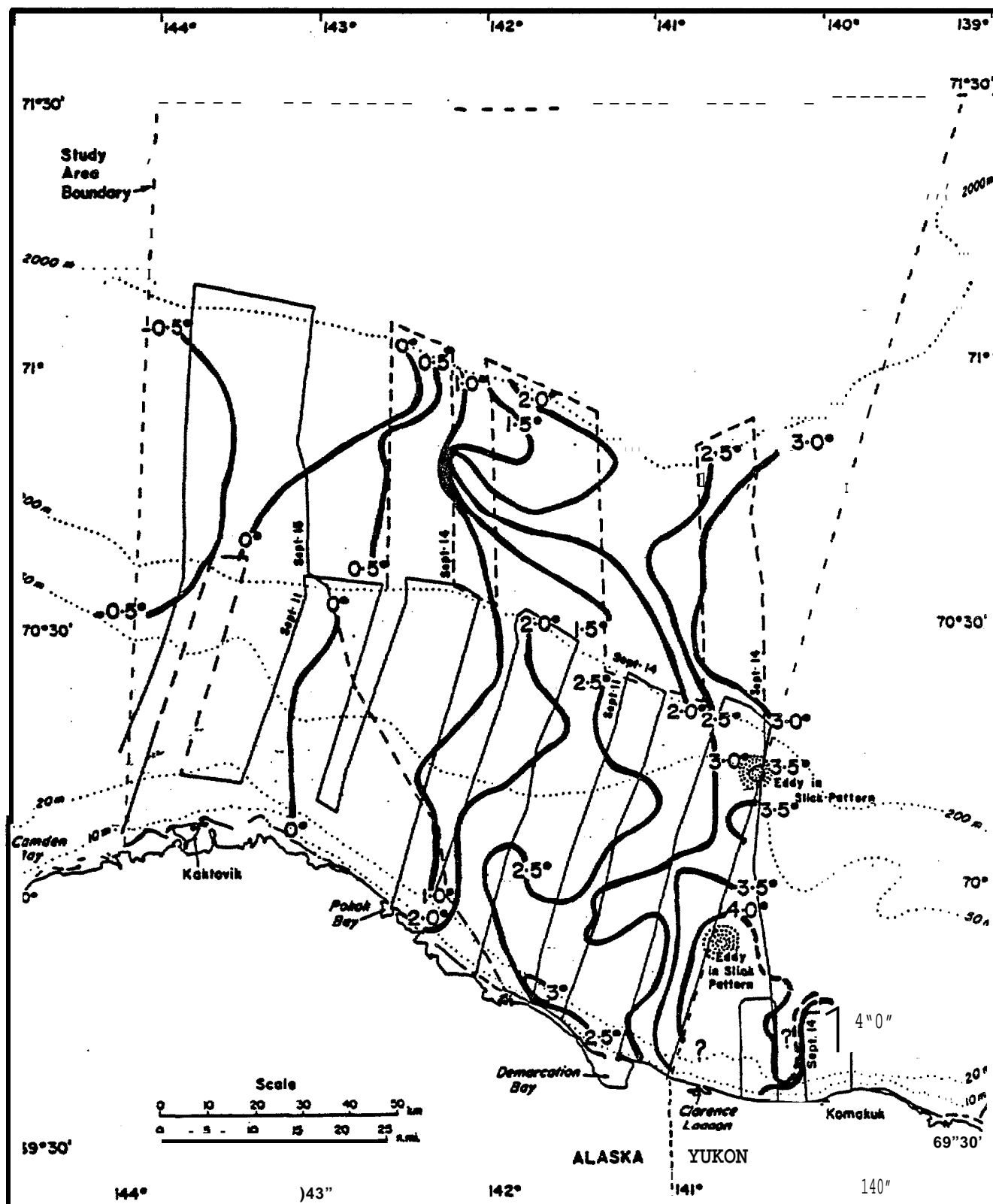


FIGURE 34. Distribution of sea surface temperature (°C) in the Eastern Alaskan Beaufort Sea on 10-14 September 1986, as measured with an airborne radiation thermometer. The thinner lines are the aircraft transects.

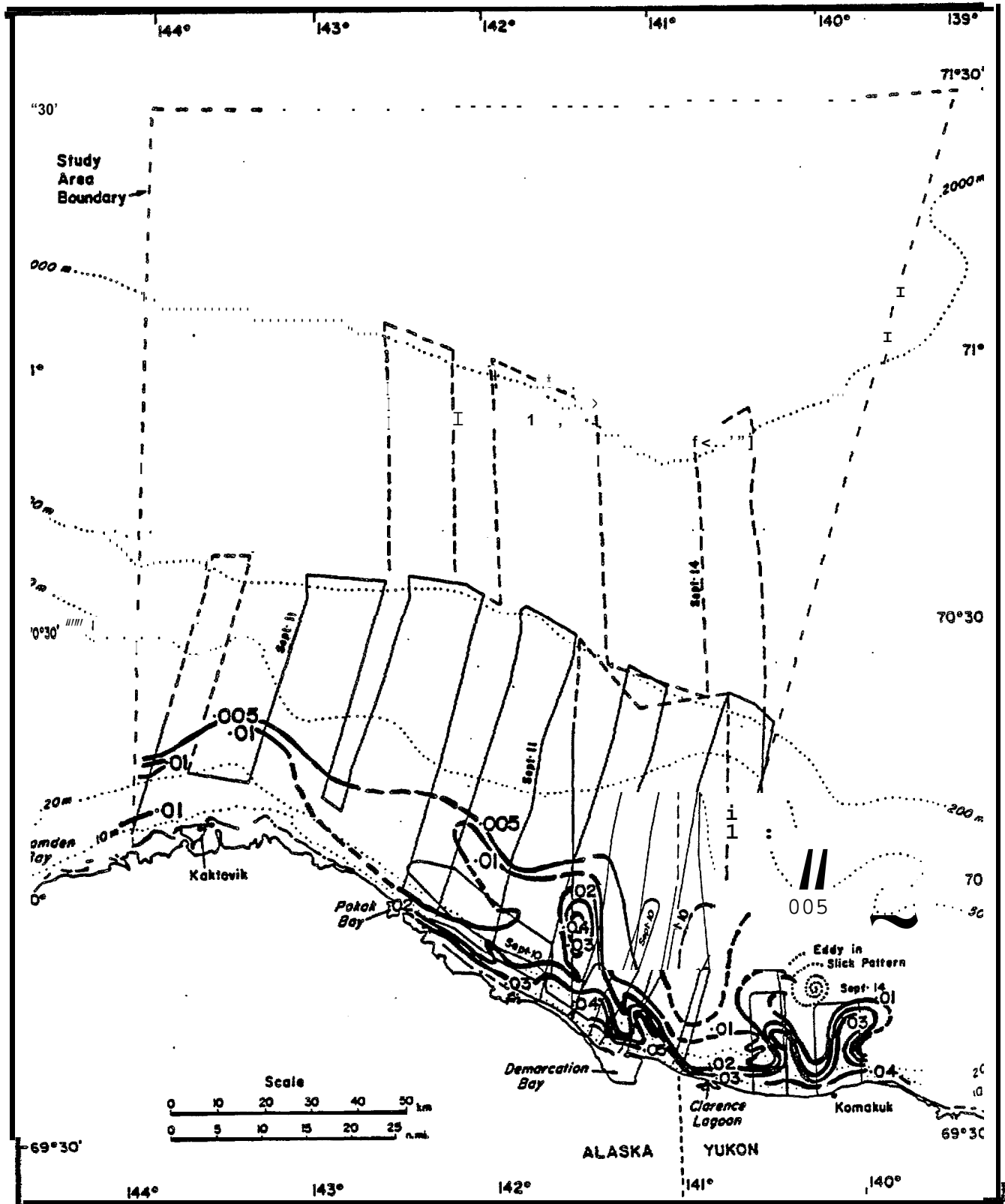


FIGURE 35. Distribution of the Red Reflectance Index R640 in the Eastern Alaskan Beaufort Sea on 10-14 September 1986, as measured with the IOS spectrometer. R640 increases with increasing turbidity of the upper water column. The thinner lines are the aircraft transects.

The broadest-scale fronts generally were associated with the **inner** boundary **of** the offshore Mackenzie Water in the eastern part of the study area, particularly in 1985. Comparatively strong fronts also occurred over the continental **shelf**, but varied considerably in location. In mid-September 1985, a strong thermal front occurred over the 50 m **isobath**, while in early September 1986 north-south fronts were more common. **In** 1986, fronts occurred along the boundaries of the warmer, turbid water in the nearshore and inner shelf areas. Fronts were also observed farther offshore between cold Arctic Water to the west and remnants of Mackenzie Bay water to the east.

### Subsurface Distributions

Analysis of Pre-1985 Historical Data.--As part of the review and analysis of physical oceanographic data collected by previous investigators within the study area (**Fissel et al.** 1985), several data sets spanning the years 1951-1978 were subjected to further analysis (Fig. 38, Table 4). Vertical sections of temperature and salinity (T/S) have been produced for those data sets collected **along** transects extending roughly perpendicular to shore. The vertical sections (Fig. 39-41) represent summer conditions, i.e. August or September. At depths of 250 m or more, temperatures and salinities are near 0°C and 34 psu, which are representative of the top of the Atlantic Water layer (see **Fig. 9** on **p. 24**). Above 250 m depth, the T/S **data** show more structure with strong horizontal and vertical gradients.

The vertical sections were examined **for** evidence of **upwelling**. **Upwelling** **on** the shelf is characterized by the presence of cold, saline **water** that originates at greater depths over the continental **slope** and rise. The **upwelled** waters are also characterized by high **levels** of dissolved oxygen and nutrients, which account for their enhancement of primary production in the **shelf waters** (see Fig. 11 on p. 27). **Due** to the absence or sparseness of nutrient data **from** most cruises, the most general indicator for **upwelling** is the salinity contour of 32 **psu**. This contour represents the lower limit of the upper layer **pycnocline** over the continental slope, and does not **always** occur over the shelf (Mountain 1974).

An examination of the historical cross-sections suggests that **upwelling** occurred during the summers of 1959, 1972 and 1978. In two vertical sections available for 1957, **along** with those for 1951, 1958 and 1971, the salinity distribution provided no clear evidence of **upwelling**. Note, however, that the phosphate and oxygen distributions available for 1971 did suggest that **upwelling** was occurring. In 1951 and 1958, an upward tilt of the 32 psu salinity contour toward shore could be inferred over **the** inner portion of the continental slope and shelf edge, suggesting the possibility of weak **upwelling**. The 1977 cross-sections revealed upwelling characteristics over the slope and **shelf** break, but not extending throughout the inner shelf zone. Thus, of the nine cross-sections considered, there were three instances of strong **upwelling** conditions, four of lesser or an indeterminate degree of **upwelling**, and two (both in 1957) in which **upwelling** was not present.

The results suggest that **upwelling** may occur frequently in the Eastern Alaskan Beaufort Sea. Coastal **upwelling** is produced by easterly winds (the dominant wind direction for this area) combined with sufficient open water to

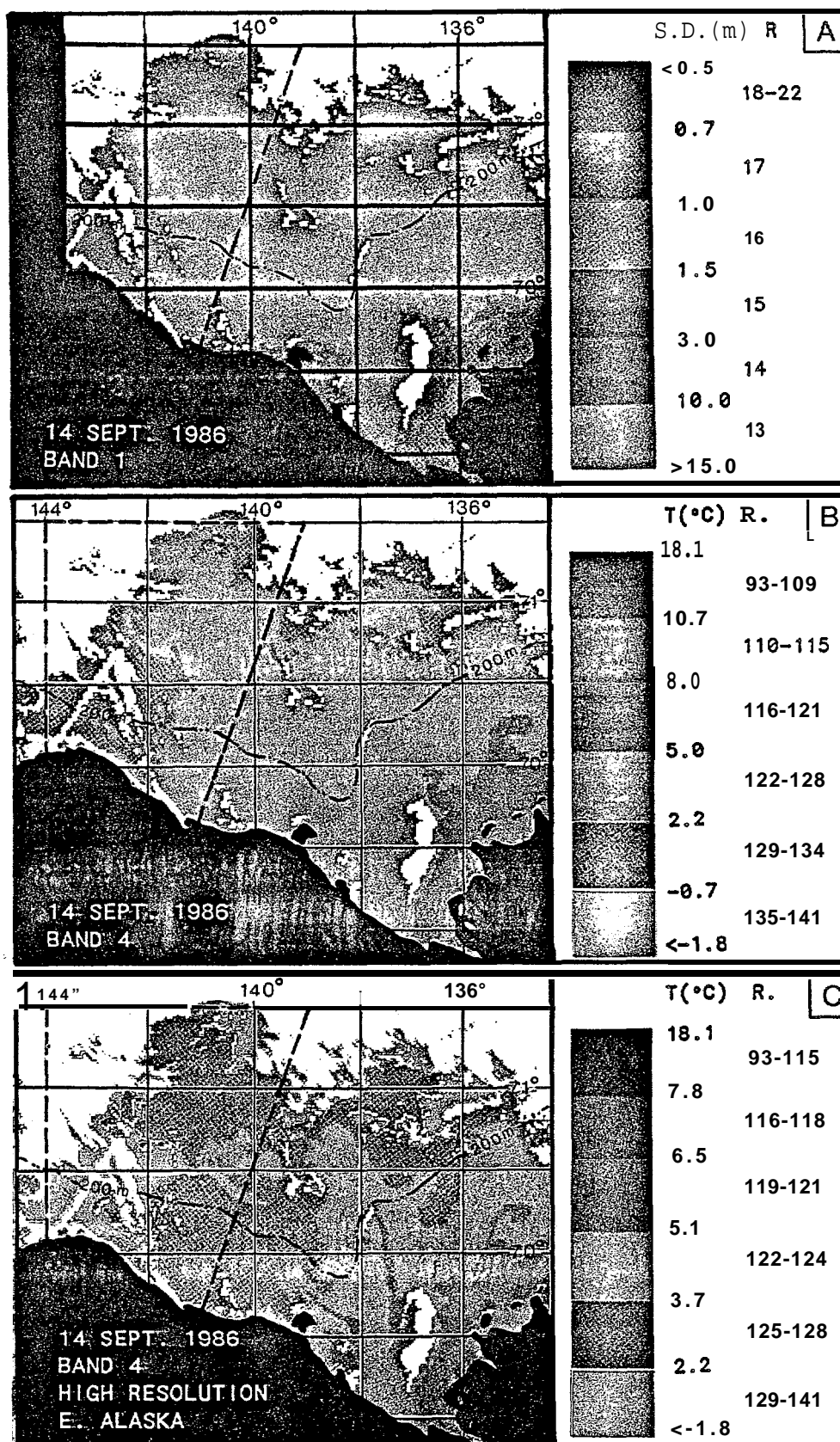


FIGURE 36. Satellite data for 14 September 1986 derived from the AVHRR sensor on the NOAA-9 satellite. A false color display is used to depict patterns of (A) surface reflectance - band 1, (B) surface temperature - band 4, and (C) surface temperature - band 4, reprocessed for high resolution within the official study area (outlined by dashed lines). Accompanying the images is the range of pixel radiance values (R), and their corresponding secchi depth (S.D.) and temperature (T, °C) ranges, for each color.





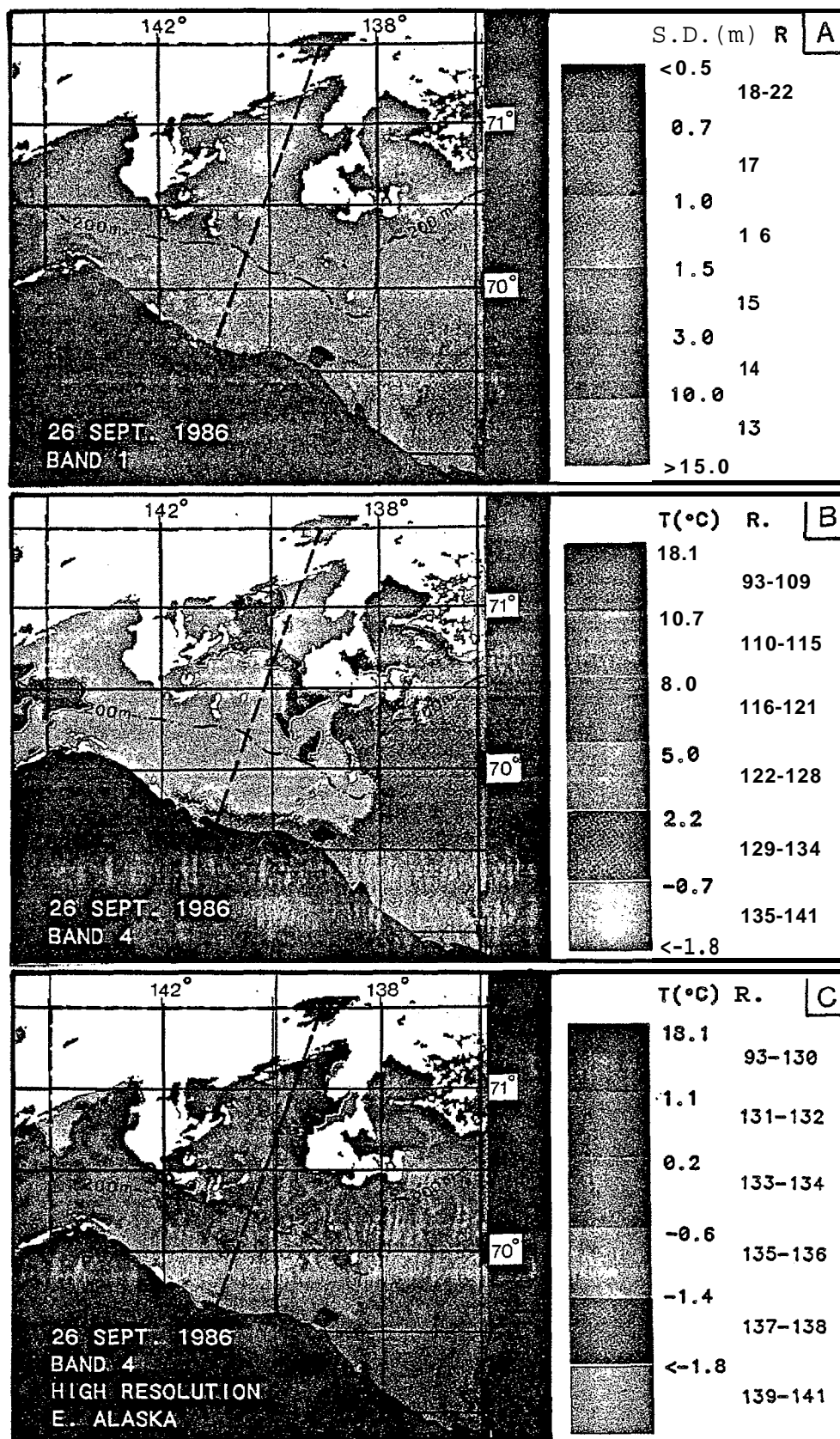


FIGURE 37. Satellite data for 26 September 1986 derived from the AVHRR sensor on the NOAA-9 satellite. A false color display is used to depict patterns of (A) surface reflectance - band 1, (B) surface temperature - band 4, and (C) surface temperature - band 4, reprocessed for high resolution within the official study area (outlined by dashed lines). Accompanying the images is the range of pixel radiance values (R), and their corresponding secchi depth (S.D.) and temperature (T, °C) ranges, for each color.



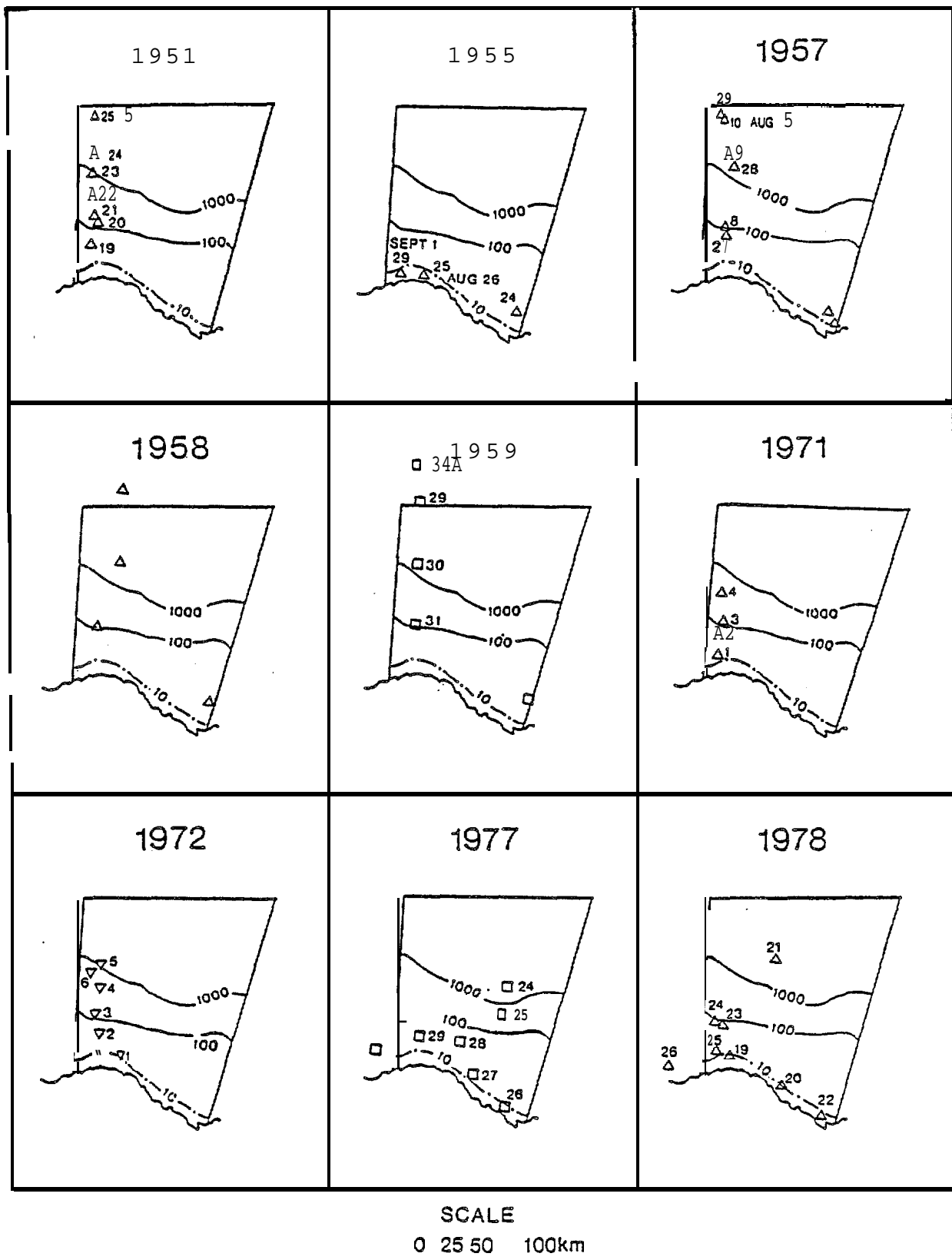


FIGURE 38. Locations where oceanographic data were collected within the study area before 1985 (cf. Table 4). These data sets were used to prepare vertical cross-sections of temperature and salinity (Fig. 39-41).

Table 4. Summary of **hydrographic** data collected in the study area, 1951-78.

Year	Dates	Vessel	Comments
<b>1951</b>	23-24 <b>Aug</b>	Burton Island	7 stations along <b>143°40'W</b>
1955	25 <b>Aug-1 Sept</b>	Northwind	3 stations along shore
1957	5-19 <b>Aug</b>	Atka	6 stations along <b>143°30'W</b>
1958	1 Sept	Burton Island	3 stations along <b>143°W</b>
1959	4-5 <b>Sept</b>	Staten Island	4 stations along <b>143°30'W</b>
1971	<b>20-21 Aug</b>	Glacier	4 stations along <b>143°30'W</b>
<b>1972</b>	4-5 Aug	Glacier	4 stations along <b>143°30'W</b>
1977	25-29 Aug	Glacier	6 stations <b>in area</b>
1978	1-25 Sept	Northwind	7 stations <b>in area</b>

provide a suitable degree of wind fetch. The Eastern Alaskan Beaufort Sea 'is more likely to experience **large** wind fetches from the east than the west, given the tendency for sea-ice to remain farther from shore to the east. Thus, **upwelling** may be more frequent in our study area than in the remainder of the Alaskan Beaufort Sea.

Analysis of Subsurface Distributions, 1985-86. --The CTD data were examined to study the distribution of water types **at depth**, and to search for possible relationships between **surface** and subsurface water mass distributions. In analyzing the 1985 CTD data (Fig. 42), the measurements on' transects 1 and 2 were considered separately from those on transect 4. The **latter** transect was occupied 8 to 13 days after transects 1 and 2, **and an** intense westerly wind event occurred between these times (Fig. 7). In 1986, **CTD** data were collected over an extended period (4-19 **Sept**) in which winds were generally weak to moderate in magnitude and variable **in** direction.

In the following discussion of subsurface distributions, the water **column** of the study area is divided **into** three vertical zones (Fig. 43). Extending to the surface is the upper layer, characterized by vertically uniform **water** properties. Below this is the **pycnocline**, which extends to depths of 15 to 32 m. Within the **pycnocline**, water properties change rapidly with depth, usually involving very intense gradients immediately beneath the upper layer, and with lesser vertical gradients at increasing depths.. The lower layer occupies the deepest portion of the water column, extending to the bottom. Here vertical gradients in density (and salinity) are either weak or non-existent but large variations in temperature can occur.

**1985 Results:** The 1985 vertical cross-sections of temperature and salinity (Fig. 44) provide further information on differences in the properties of the surface **layer** from the nearshore zone to the edge of the continental shelf. Over the outer shelf, where water depths are 50 to 100 m, a well-mixed upper **layer** was present from the surface to approximately 5 m. This layer was characterized by higher temperatures (1.5 to **2.5°C**) and **lower** salinities (23 to 26 psu) than those in the top layer closer to shore. Closer

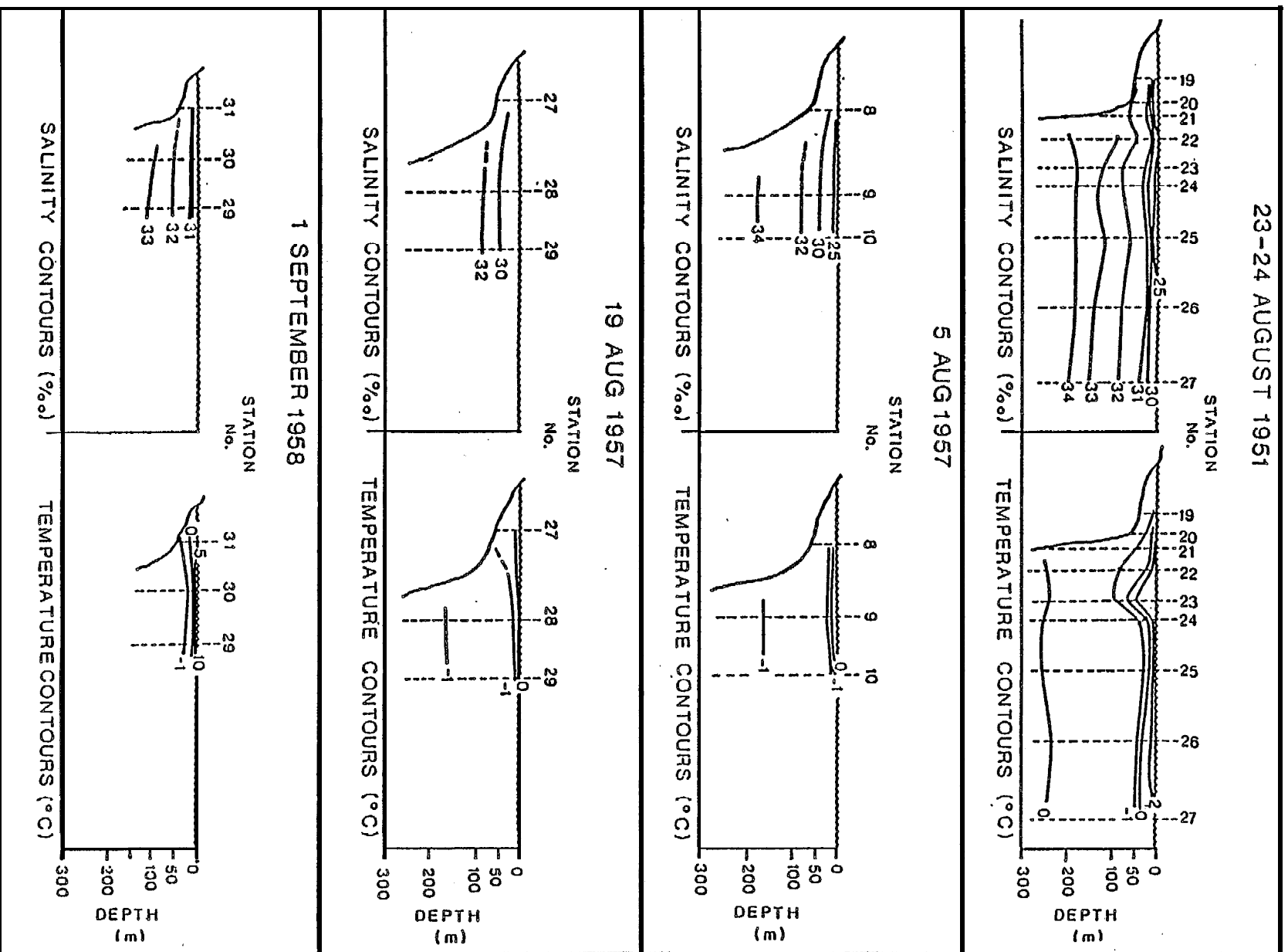


FIGURE 39. Vertical cross-sections of temperature and salinity from 1951, 1957 (2 cases) and 1958.

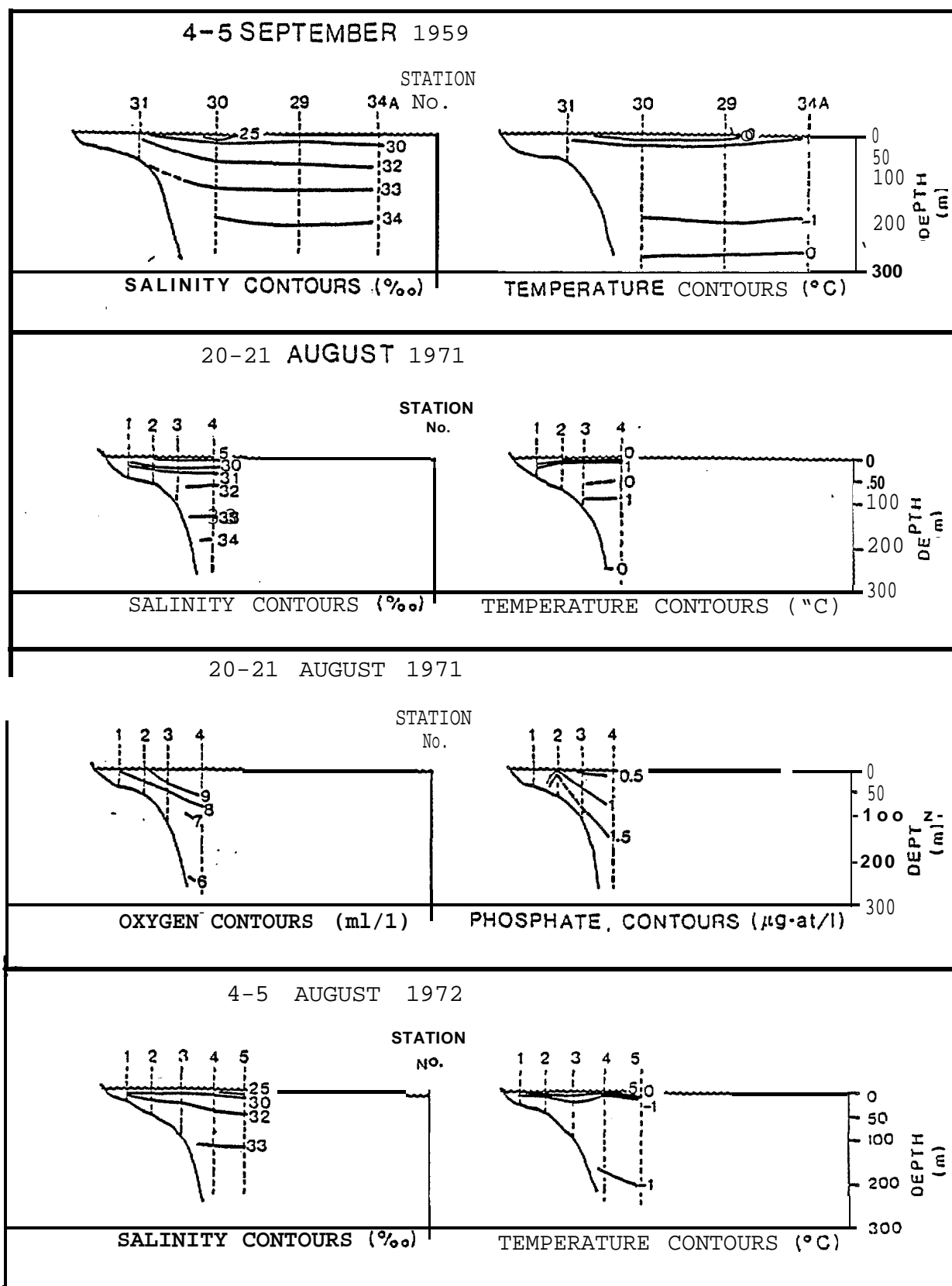


FIGURE 40. Vertical cross-sections of temperature and salinity from 1959, 1971 and 1972. For 1971, oxygen and phosphate data are also shown.

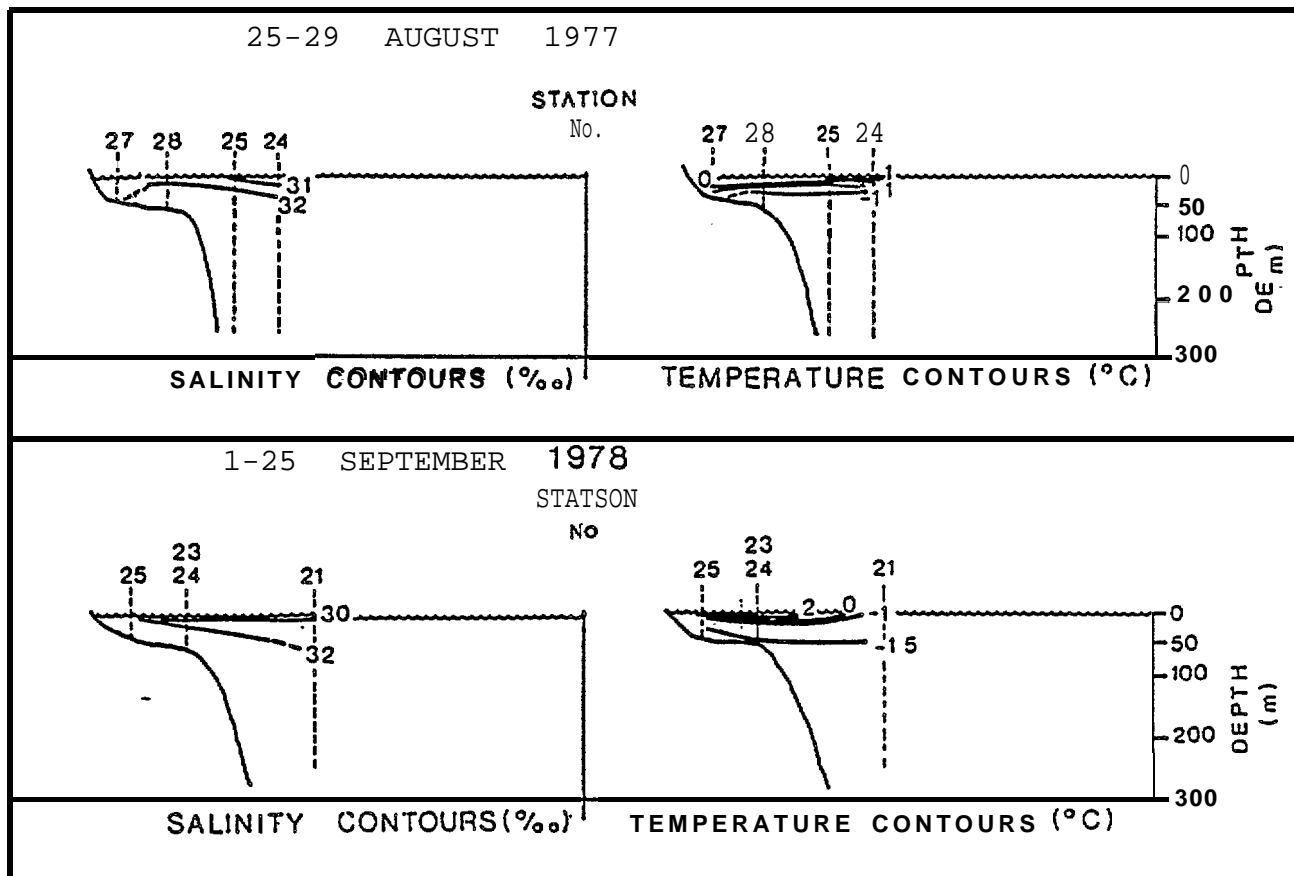
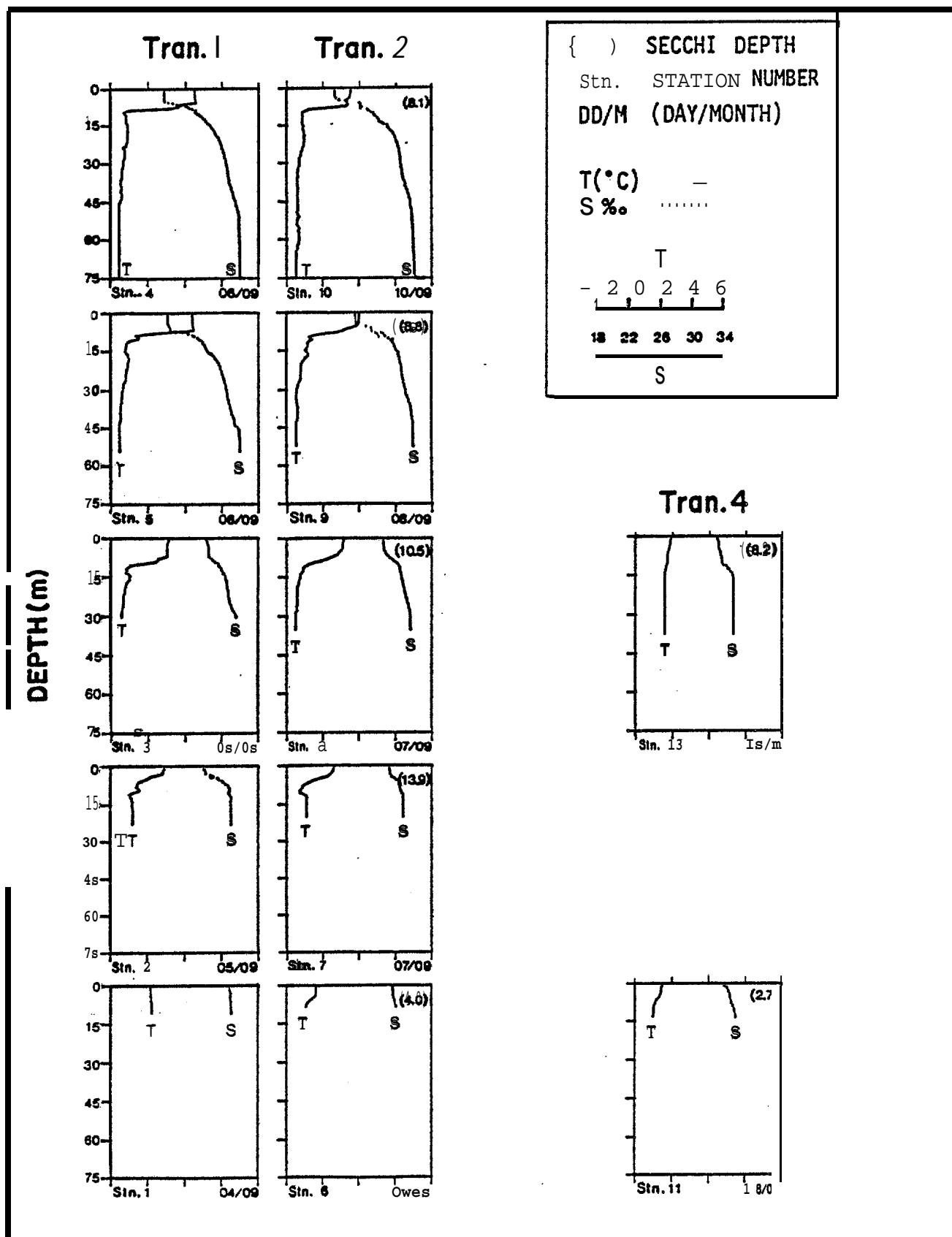


FIGURE 41. Vertical cross-sections of Temperature and salinity from 1977 and 1978.

to shore, the upper layer was characterized by progressively reduced temperatures and increased salinities. The depth of the mixed layer was also reduced to 3-4 m at the shallower stations (stations 2, 7 and 8; see Fig. 43). Note, however, that at station 3 located at 31 m depth, the mixed layer extended to 7 m depth. Also, within the nearshore zone at water depths of 10 m or less, the water column had uniform properties to the bottom at station 1 off Kaktovik. However, at nearshore station 6, located 36 km to the east, the mixed layer extended to 5 m depth, with warmer and slightly more saline water over the 5-10 m depth range.

The CTD data from transects 1 and 2 (4-10 Sept 1985) showed that the water properties at measurement depths in excess of 30 m were characteristic of Arctic. Water having an offshore origin (temperatures  $<1.5^{\circ}\text{C}$ ; salinities  $>31$ ). Along transects 1 and 2, the upward tilt of the temperature and salinity contours near the coast (Fig. 44) is consistent with historical data (e.g. Fig. 11, 39-41) and is indicative of a shoreward transport of Arctic Water from the edge of the continental shelf to nearshore and inner shelf areas. These results would be expected from coastal upwelling driven by winds directed parallel to the coast, with the coast to the left of the wind direction (i.e. easterly winds). The winds were predominantly from the east during the measurement period (5-10 Sept 1985) and the preceding three weeks, supporting the hypothesis of coastal upwelling.





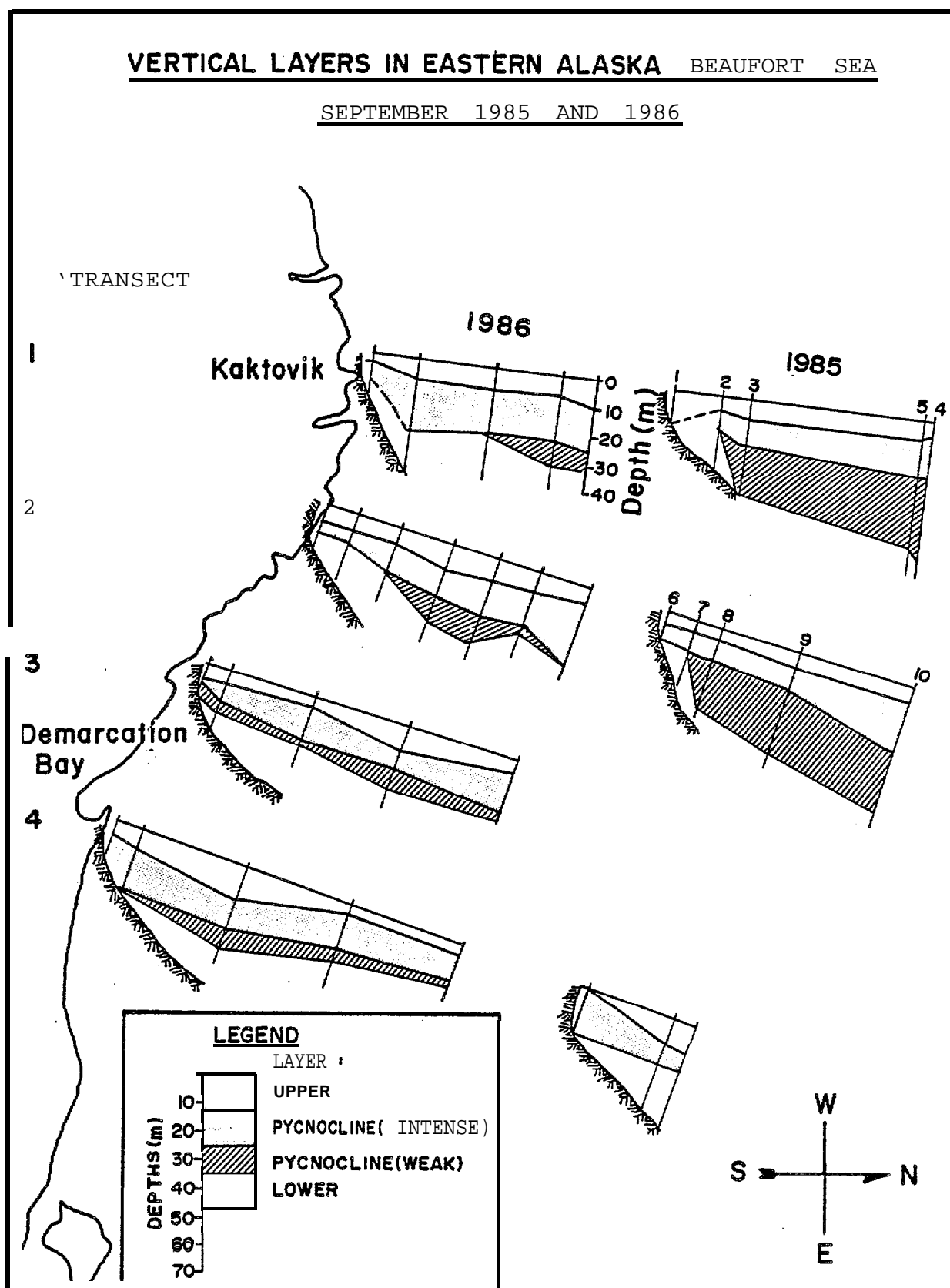


FIGURE 43. Vertical cross-sections illustrating the depths of the zones that make up the water column; based on vertical distributions of temperature, salinity and density in September 1985-86.

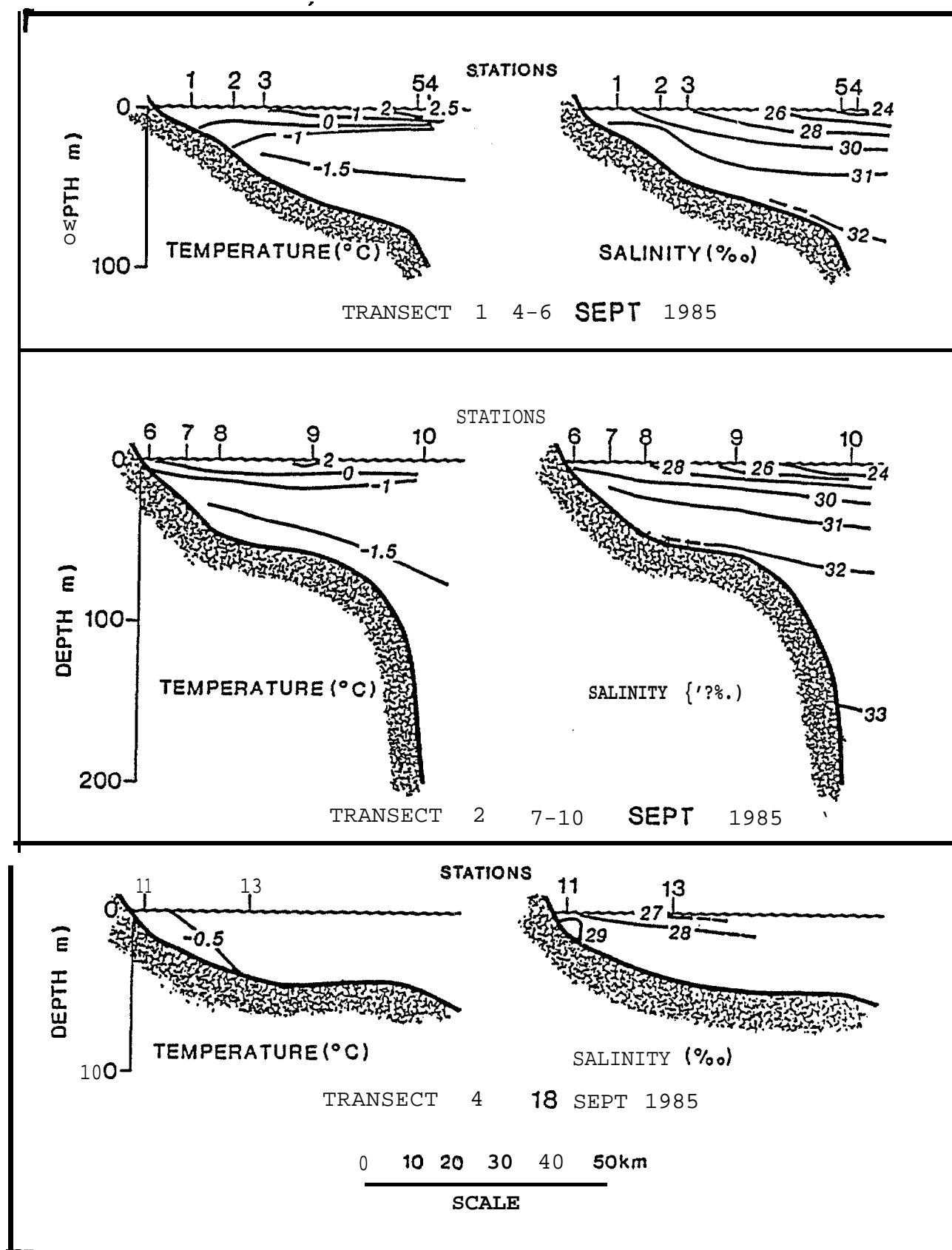


FIGURE 44. Vertical cross-sections of temperature and salinity along boat transects 1, 2 and 4 in September 1985.

In nearshore areas, there was evidence of other processes besides coastal upwelling. At station 1, the temperature of the water column was just over  $0.0^{\circ}\text{C}$ , considerably warmer than the temperature of the deeper water of comparable salinity found farther offshore (Fig. 44). The source of the additional heat within the water column at station 1 was probably the warmer water discharged from the extensive network of lagoons east of Kaktovik. Airborne surveys on 5-6 and 13 September (Fig. 23, 25) showed a narrow coastal band with surface temperatures of  $0.5$  to  $2^{\circ}\text{C}$ . Discharges are most likely to occur with easterly winds due to reduced water levels along the coast associated with the offshore transport of near-surface waters. At station 6, also located near the coast, the degree of warming of the water column was considerably less than at station 1. This suggests that the source of warming of some nearshore waters may be localized. Station 1 was closer to a complex of coastal lagoons than was station 6 (Fig. 16).

**1986 Results:** Based on the CTD data of 4-19 September 1986 (Fig. 45, 46), we prepared vertical cross-sections of temperature and salinity on four onshore-offshore transects (Fig. 47, 48). The well-mixed upper layer, although occurring at similar depths as in 1985, differed considerably in temperature and salinity. Along the outer shelf portions of the westernmost transects (1 and 2) upper layer temperatures were lower (ranging from  $<0$  to  $2^{\circ}\text{C}$ ) and salinities were higher (25-26 psu) in 1986 than in 1985. This reflected the weaker influence of Mackenzie Bay water in 1986. Only at the outermost station on the most easterly transect were the upper layer salinities  $<25$  psu; in 1985, salinities  $<25$  psu extended west to transect 1. In contrast, over the inner half of the shelf, the upper layer was warmer and less saline than in 1985. On transects 1 and 2, upper layer temperatures over the inner shelf were typically  $1.8$  to  $2.5^{\circ}\text{C}$ , approximately  $1^{\circ}\text{C}$  warmer than in the previous year. Similarly, in 1986 upper layer salinities there ranged from 25.5 to 27.5, approximately 1.5 to 2 psu lower than in 1985. On the inner parts of the easterly transects (3 and 4), the upper layer was characterized by even warmer temperatures. ( $2-4^{\circ}\text{C}$ ) in 1986. Salinity levels over the inner shelf changed little from west to east.

Within and below the seasonal pycnocline, cold saline Arctic water was present over most of the continental shelf. At depths exceeding 20 m, temperatures were generally less than  $0^{\circ}\text{C}$ , and salinities exceeded 30 psu. However, at and beyond the shelf edge, much warmer water was present in the form of a subsurface temperature maximum, extending from depths of 20 to 100 m. This warm water apparently originated in the Bering Sea, as the temperature-salinity characteristics (temperature  $>0^{\circ}\text{C}$ , salinities 30.0-32.5 psu) were identical to those of the Bering Sea subsurface waters, which are known to propagate eastward along the continental shelf edge of the Beaufort Sea as a subsurface temperature maximum (Mountain 1974). However, the presence of Bering Sea Water as far east as the study area is a rare occurrence. In the 1985 data (this study) and the earlier 1951-78 data reanalyzed here (Fig. 39-41, 44) there was no indication of a pronounced subsurface temperature maximum within the study area.

In the core of the warm Bering Sea water, very high temperatures were measured on the westernmost transects (Fig. 47). On transect 1, a maximum temperature of  $3.4^{\circ}\text{C}$  occurred at 34 m depth at station t1-5 over the inner continental slope (Fig. 47, 49). On transect 2, the warmest temperatures were

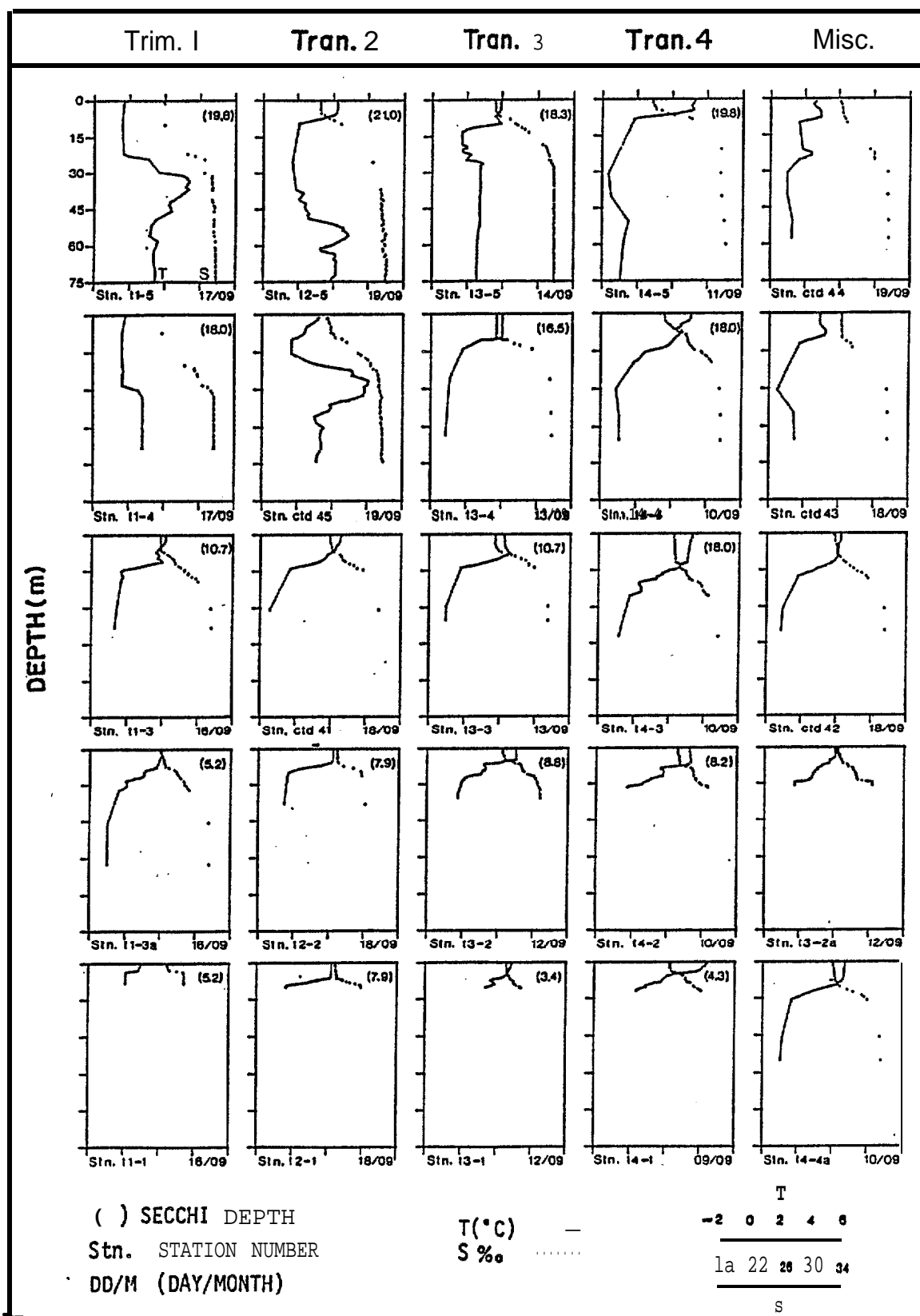


FIGURE 45. Temperature and salinity profiles measured at the September 1986 CTD stations on boat transects 1, 2, 3 and 4. The presentation is as for Fig. 42.

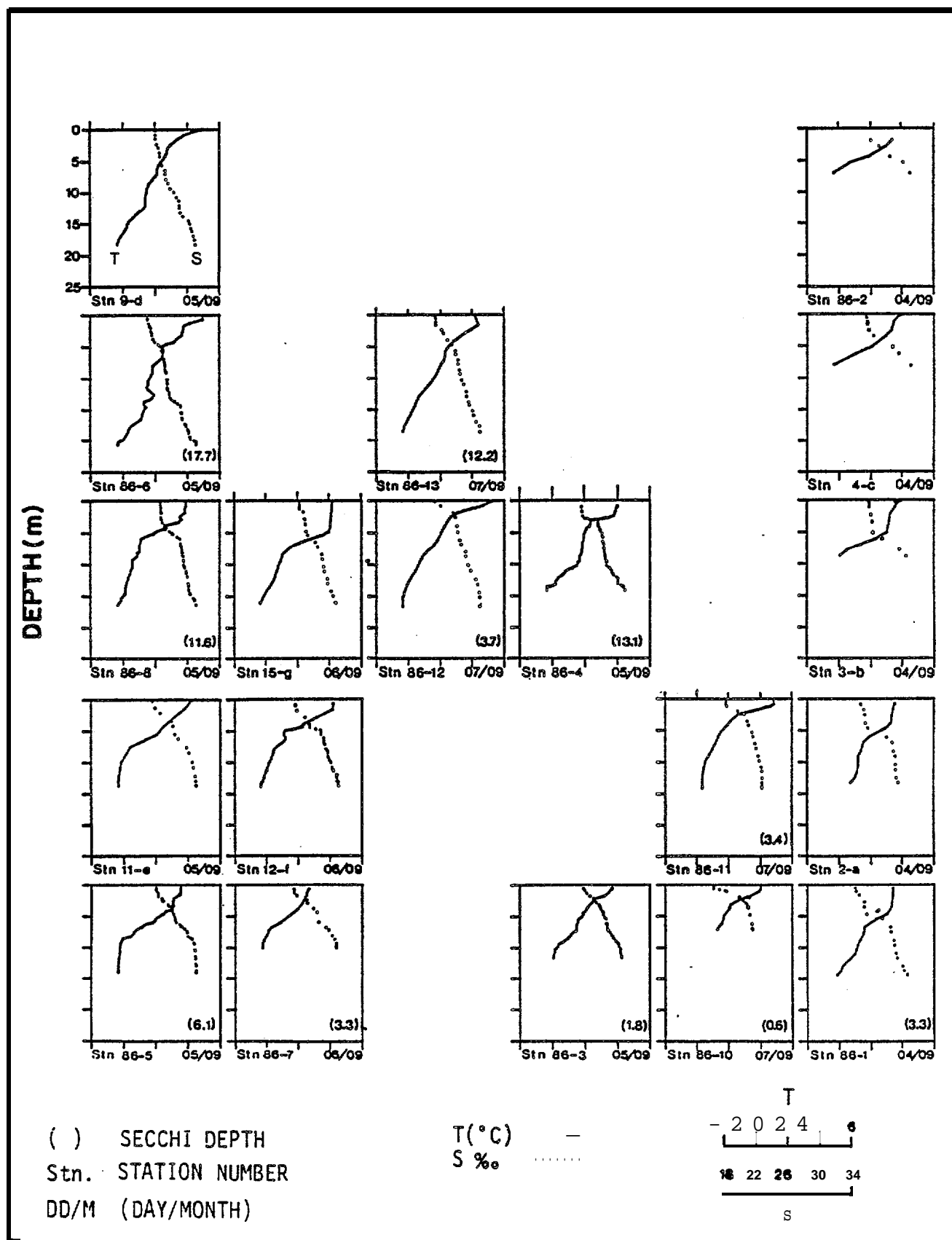


FIGURE 46. Temperature and salinity profiles measured at CTD stations located on the inner shelf in the eastern half of the study area, September 1986. The presentation is as for Fig. 42.

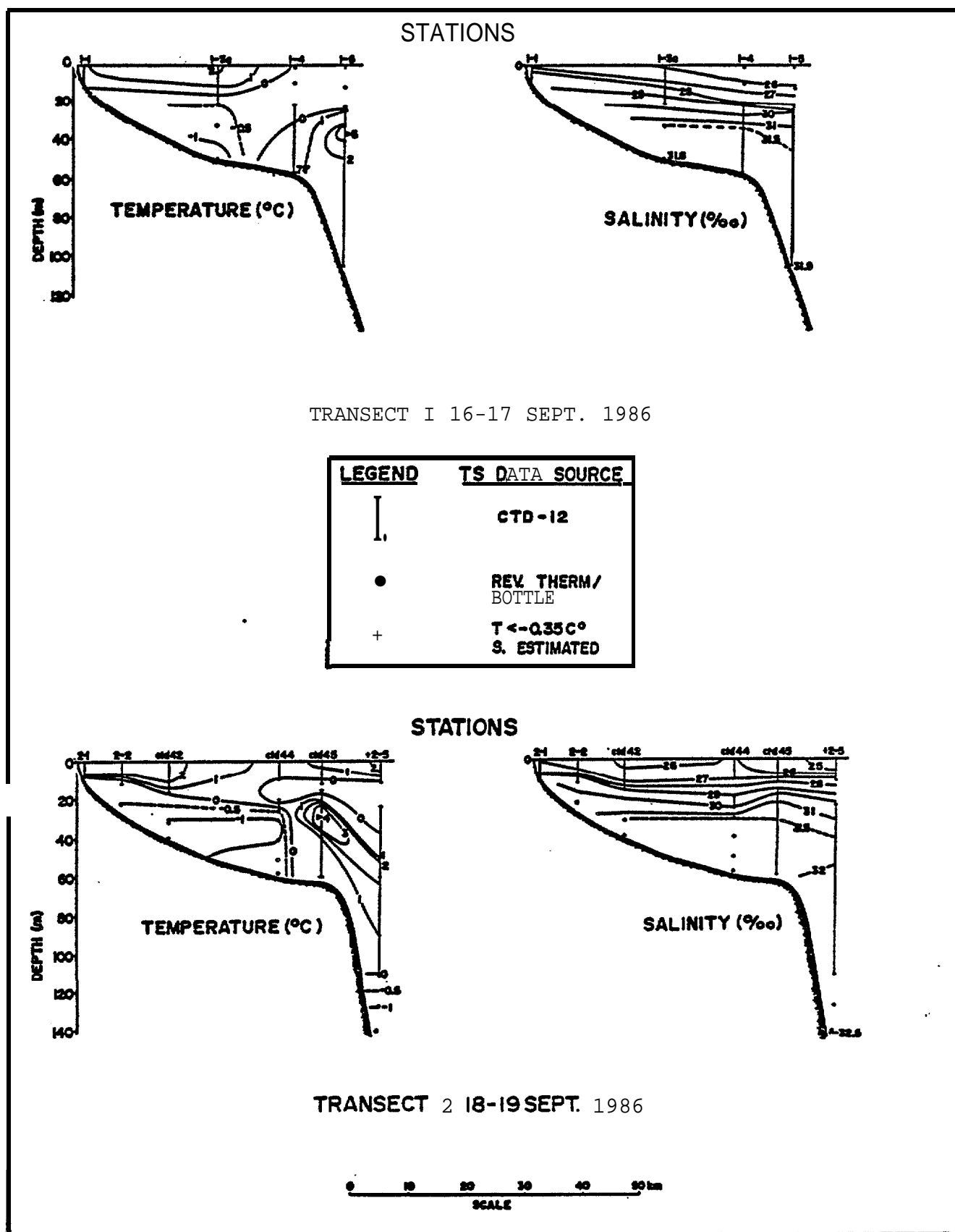


FIGURE 47. Vertical cross-sections of temperature and salinity along boat transects 1 and 2, occupied 16-17 September 1986, and 18-19 September 1986.

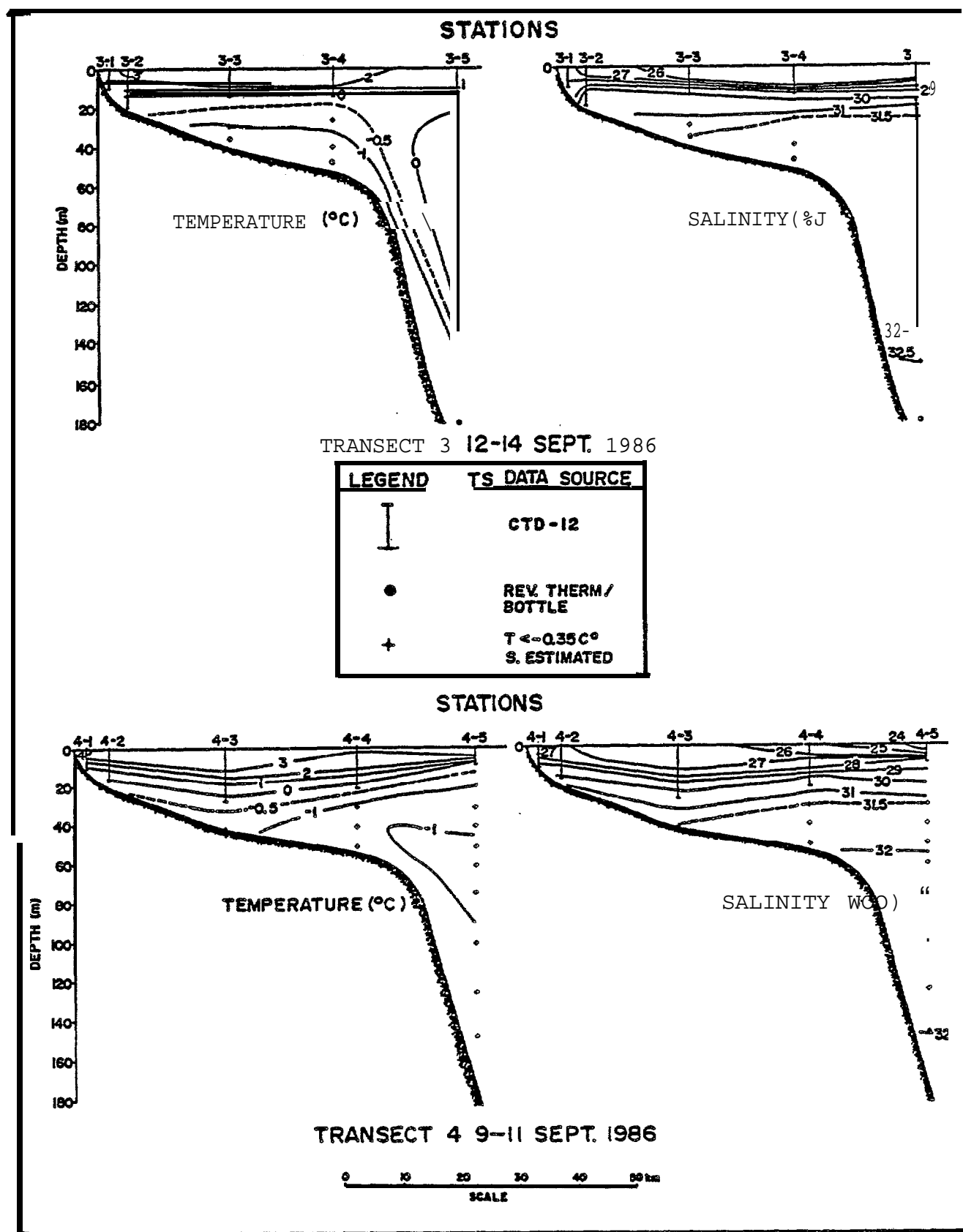
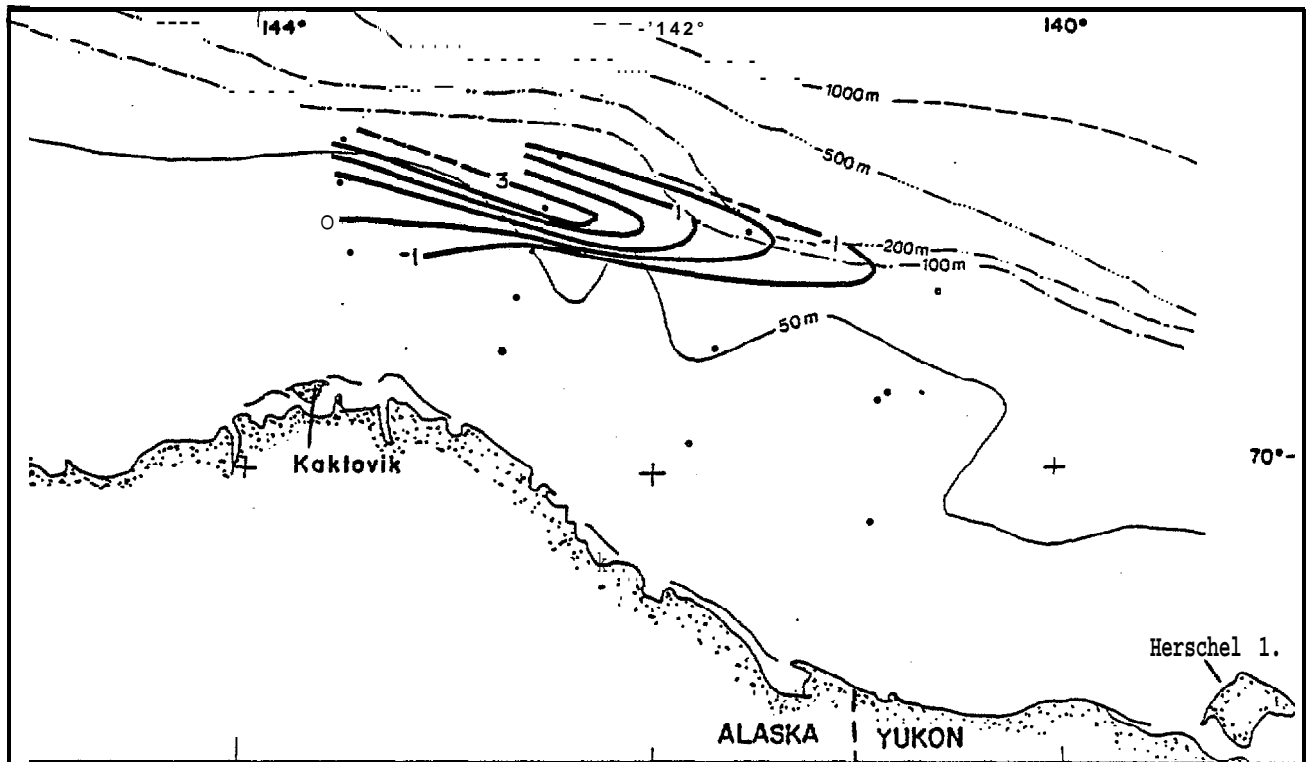


FIGURE 48. Vertical cross-sections of temperature and salinity along boat transects 3 and 4, occupied 12-14 September 1986, and 9-11 September 1986.



\* FIGURE 49. Map of temperature on the 31.4 psu salinity surface, derived from the September '1986 CTD data. The solid circles de-note CTD measurement locations where the 31.4 salinity was measured.

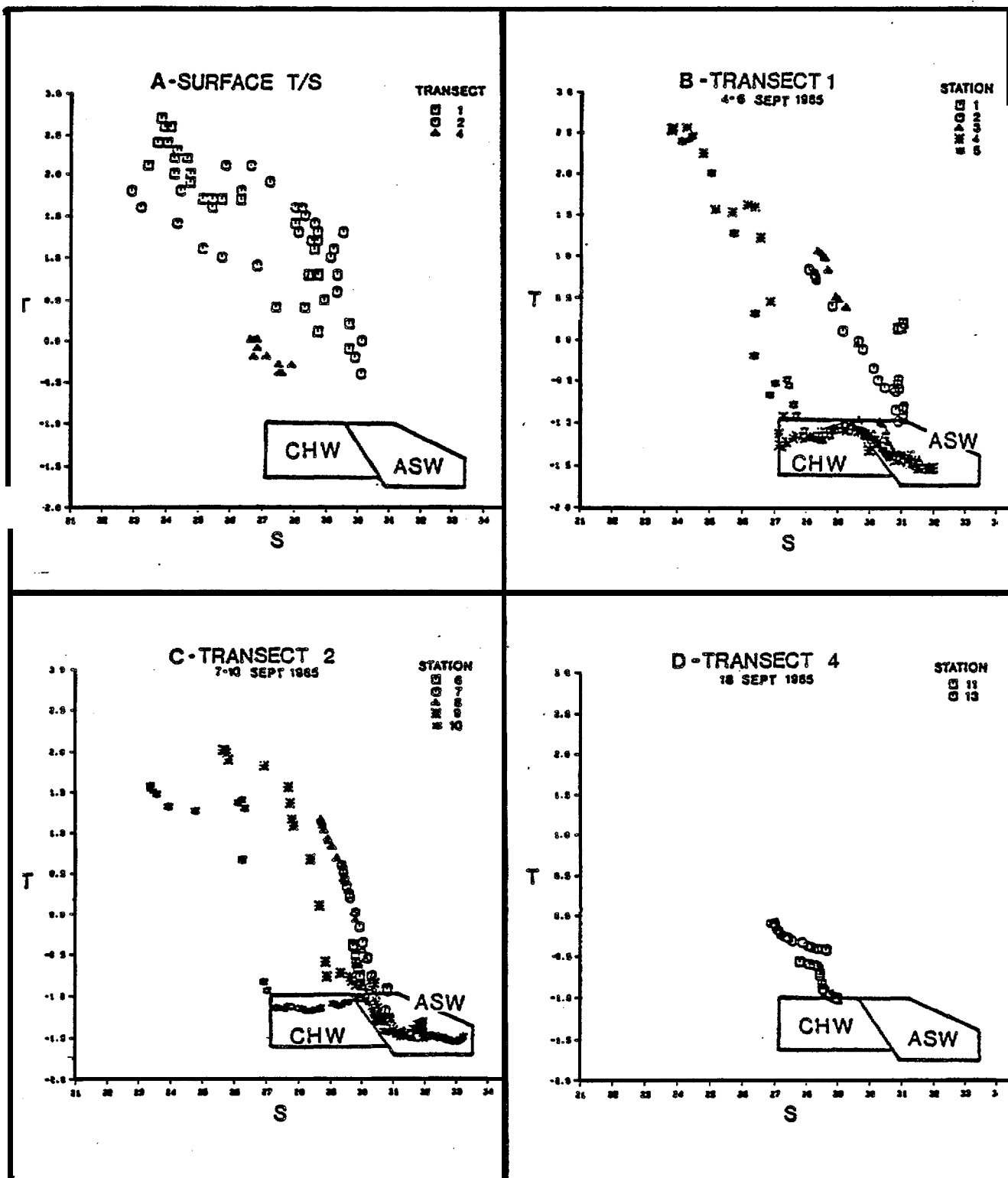
measured at station CTD 45, located near the outer edge of the continental shelf, where a maximum temperature of  $4.1^{\circ}\text{C}$  was measured at 27 m depth. At station t2-5, located over the continental slope on transect 2, the maximum temperature was lower ( $2.9^{\circ}\text{C}$ ) and occurred at a considerably greater depth, 56 m. Farther east on transects 3 and 4, the warm Bering Sea water was present but with much diminished prominence. It occurred at the "outermost station (t3-5) on transect 3 as a deep temperature maximum at 25 to 135 m, with a maximum of  $0.9^{\circ}\text{C}$  at 27 m depth. On transect 4, the maximum was at depths 45 to 65 m, with a maximum value of only  $-0.5^{\circ}\text{C}$ , at 50 m.

In 1986, unlike 1985, the Arctic water over the inner shelf did not have the very cold and saline characteristics that occur at the shelf edge and in the deep basin of the Arctic Ocean. The isopleths did not show any clear evidence of an upward tilt toward the coast in 1986, which would have been indicative of upwelling. In 1985, upwelling was inferred for boat transects 1 and 2 (Fig. 44).

#### Water Mass Analysis

Type's of Water Masses.--The temperature/salinity (T/S) characteristics revealed by the surface measurements and the CTD data (Fig. 50-52) can be used to infer the origins of the various water mass types present beneath the surface layer in the Eastern Alaskan Beaufort Sea. Within the lower part of the water column, two major categories of water mass types are evident:





**FIGURE 50. Temperature/salinity (T/S) diagrams of the September 1985 physical oceanographic data: (A) surface T/S on boat transects 1, 2 and 4; (B) transect 1 profile data; (C) transect 2 profile data; and (D) transect 4 profile data. The boxes on the plots represent the T/S characteristics of Cold Halocline Water (CHW) and Arctic Surface Water (ASW).**

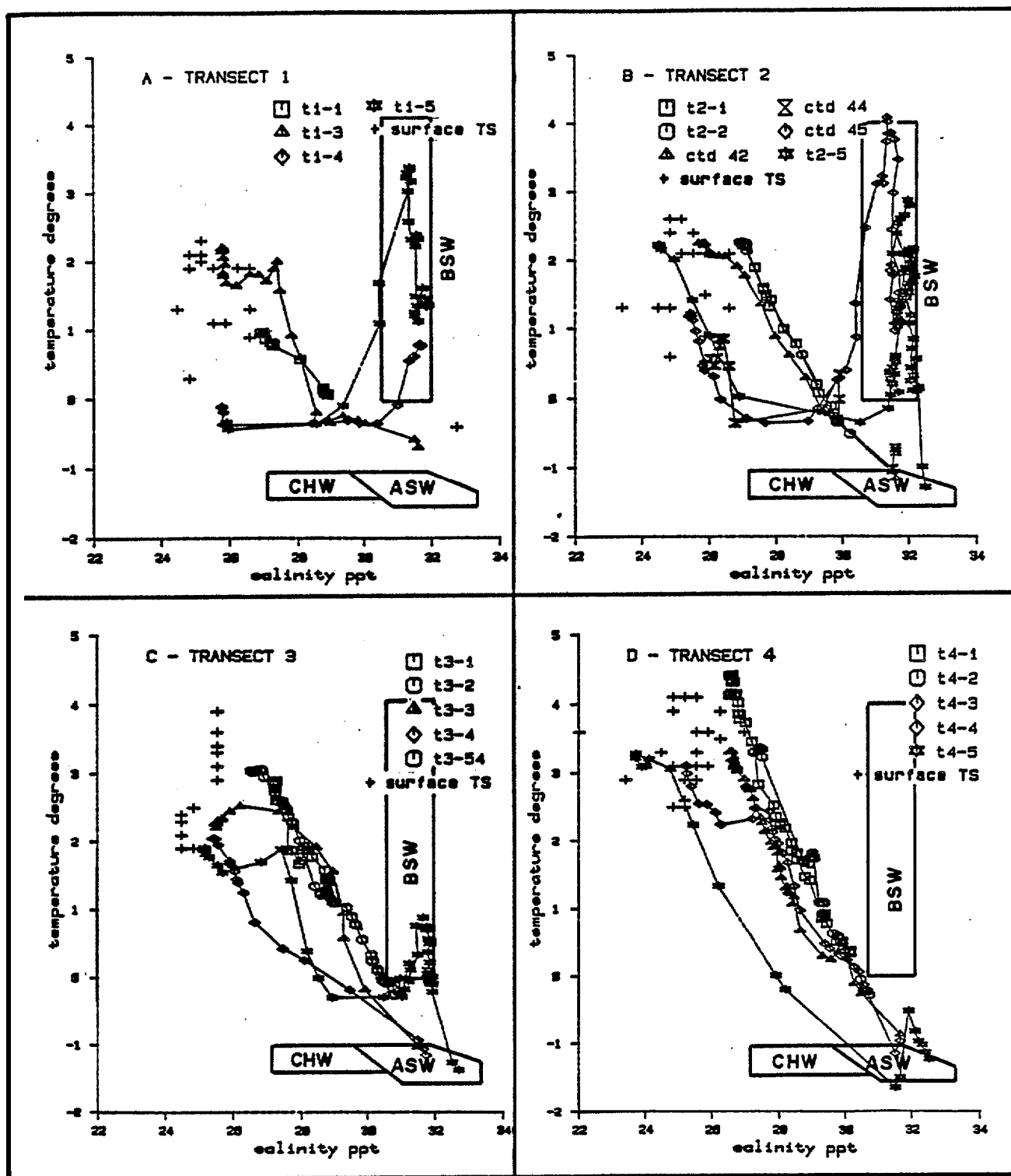


FIGURE 51. Temperature/salinity (T/S) diagrams of the September 1986 physical oceanographic data from broad-scale transects: (A) on boat transect 1; (B) on boat transect 2; (C) on boat transect 3; (D) on boat transect 4. Presentation is as for Fig. 50, with the addition of Bering Sea Water (BSW).

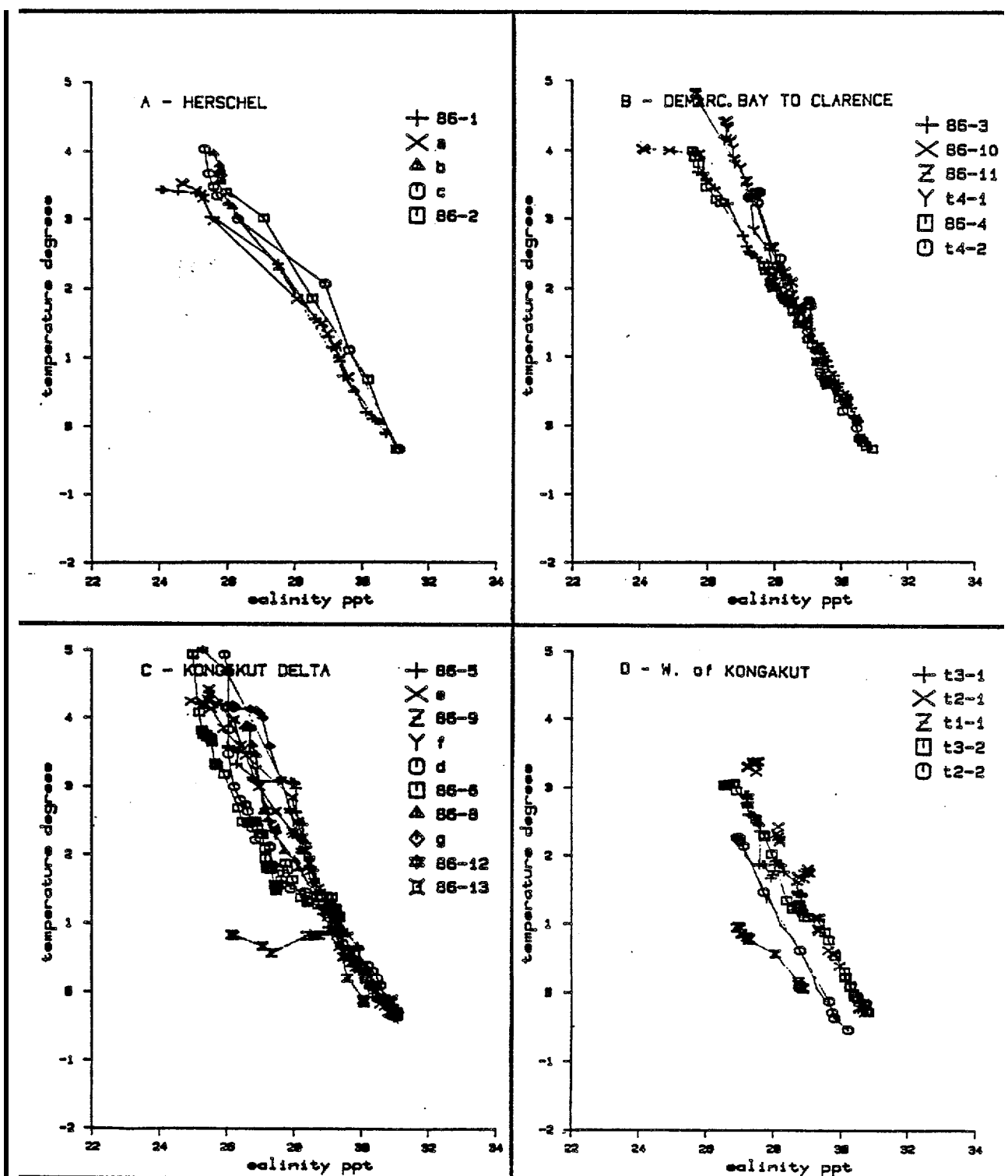


FIGURE 52. Temperature/salinity (T/S) diagrams of the September 1986 physical oceanographic data obtained at inner shelf locations: (A) for sites immediately to the west of Herschel Island; (B) for sites between Demarcation Bay and Clarence Lagoon; (C) for sites near the Kongakut Delta; and (D) for sites west of the Kongakut Delta.

1. **Arctic Surface Water (ASW)** - This water type is cold ( $<-1.0^{\circ}\text{C}$ ) and saline ( $>31$  psu) and originates within the Arctic Ocean through large scale exchanges between the waters of the Arctic Ocean's continental shelf and the underlying Atlantic Water in the deep basins of the Arctic Ocean (Aagaard et al. 1981).
2. **Bering Sea Water (BSW)** - In 1986, a second water mass was present in the lower layer of the water column. It took the form of a subsurface core of warm water extending over depths 20 to 100 m. This water mass originates in the Bering Sea; it flows north through the Chukchi Sea and then east along the outer edge of the continental shelf in the Beaufort Sea (Mountain 1974). The measured TS characteristics --temperatures exceeding  $0^{\circ}\text{C}$  over a salinity range of 30.5 to 32.0 psu--were in good agreement with the historical description of Bering Sea Water at more westerly locations (Mountain 1974). Bering Sea Water rarely reaches the study area from the west, and was not unambiguously discernible in 1985. The last recorded instance of an eastward intrusion of Bering Sea Water into the study area was in 1951. In late August 1951 the temperature maximum was  $<1^{\circ}\text{C}$  (Fig. 39), much lower than the values observed in 1986.

The upper portion of the water column consists of the surface layer and the pycnocline. Here water mass categories are less distinct, and more variable in space and time, due to active modification through surface related processes such as heat exchanges, formation and melting of sea-ice, and river discharges. Nevertheless, there is some evidence of water mass categories:

3. Cold **Halocline Water (CHW)** - This water type, associated with the pycnocline, is also cold ( $<-1.0^{\circ}\text{C}$ ) but less saline (27-31 psu) than Arctic Surface Water. It originates as a mixture of Arctic Surface Water with the cold fresh water that arises from melting of the seasonal ice over the continental shelves. Fresh water from the Mackenzie River and other local rivers may also contribute to this water type, but this could occur only after cooling of the river water to near-freezing point levels. Mixing of the melt water from 2.0 m of sea-ice with a 20 m layer of shelf water of average wintertime salinity of 32 psu (Melling and Lewis 1982) would result in a water column with 28 psu salinity at near-freezing temperature.
4. Mackenzie **River** Influenced Water - This water type has a very wide range of temperature (0 to  $18^{\circ}\text{C}$ ) at or near zero salinity. The range of possible T/S characteristics is further broadened through water mass modifications in Mackenzie Bay. Mixing with local melt water from sea ice reduces the temperature and, to a much lesser degree, increases the salinity. Absorption of heat from solar insolation raises the heat content while vertical mixing with the cold saline waters beneath decreases temperature and increases salinity. Examination of surface salinity and temperature data collected from drillships operating in Mackenzie Bay (Thomson et al. 1986) indicates that representative ranges of temperature and salinity, from mid-July to mid-August, are  $4-12^{\circ}\text{C}$  and 6-27 psu.

5. Nearshore Waters Influenced by Local **Estuarine** and Coastal Processes
  - At some CTD stations within a few kilometers of the coast, significant modifications were observed relative to the water mass types occurring farther offshore. In 1985, the TS curve for station 1 (Fig. 50B) indicated considerable warming relative to adjoining offshore waters, presumably due to local heating and discharge from the warm coastal lagoons. In 1986, cooler and in some instances less saline waters were present in the surface layer at several nearshore stations. These differences from the adjoining stations located farther offshore were most apparent at two stations west of Herschel Island (86-1 and a); station 86-10 east of Demarcation Bay; station 86-9 located east of the Kongakut Delta just off the barrier island; and station t1-1 off Kaktovik (Fig. 52). However, at other nearshore stations, comparatively warm waters were present, most noticeably at stations 86-11, t4-1, and t2-1. A more consistent feature of nearshore CTD stations was the occurrence of a very thin surface layer, a shallow but intense pycnocline, and cold, saline Arctic Water at comparatively shallow depths beneath the pycnocline. These characteristics were observed consistently at locations between the Kongakut Delta and Demarcation Bay (see 'Inshore Fine-Scale Oceanographic Features', below).

Water Masses in 1985.--The T/S diagrams for September 1985 (Fig. 50) show that the deeper portions of the water column at nearly all CTD stations either were ASW, or were indicative of mixing with ASW. However, at stations 1, 11 and 13, the T/S characteristics were not clearly related to ASW. For station 1, additional heat, likely through mixing with warm water from coastal lagoons, resulted in higher temperatures (see above). Data obtained on 18 September 1985 at stations 11 and 13 (Fig. 50) indicate that the T/S characteristics of the water column had been modified through mixing associated with the intense west winds on 15-17 September (see below).

In 1985, CHW was recognizable only at the three CTD stations nearest the shelf edge (stations 4, 5 and 10). This water type was not present over the inner shelf. Instead, the 6-20 m portion of the water column over the inner shelf appeared to consist of a mixture of ASW with the upper layer of Mackenzie Bay water found farther offshore, possibly with some contribution from the narrow coastal band of fresher warmer water.

The T/S characteristics of the surface layer (Fig. 50A) varied considerably among transects over the outer half of the continental shelf. On all transects, the influence of river water increased progressively with distance from shore, as indicated by increased temperatures and lower salinities at the north ends of the transects (Fig. 44, 50). However, the change in T/S characteristics differed among transects (Fig. 50). On transect 1, the surface T/S characteristics were reasonably consistent over the mid- and outer shelf. On transect 2, two distinct sets of T/S characteristics were present: the surface T/S curve was approximately 1° greater in temperature for a given salinity over the middle portion of the shelf (depths 30-70 m) than over water depths >70 m. The surface T/S characteristics on transect 1 were intermediate between the two surface water types occurring on transect 2. Such differences suggest that the upper layer, which was being advected westward from Mackenzie Bay, consisted of water masses that had been subjected

to differing modifications. The differences might represent varying blends of Mackenzie Bay water mixed with water of offshore origin.

In 1985, the T/S characteristics of transect 4 were much more uniform than those on transects 1 and 2. Transect 4 was confined to the inner shelf near the eastern limit of the study area and was studied following a major westerly wind event. The narrow ranges of temperatures and salinities on transect 4 indicate that much vertical mixing had occurred via wind action. However, the T/S characteristics cannot be explained **simply** as mixing of T/S **values** similar to those measured earlier on transects 1 and 2 over the inner **shelf**. Instead, the entire water **column** on transect 4 appeared to consist of **ASW** mixed with cooled (by **approx. 2°C**) upper **layer** Mackenzie Bay water, and perhaps also with **CHW** that previously was only found farther offshore. .

Water Masses in 1986.--T/S characteristics exhibited more variation in September 1986 than in **September 1985**. In the lower layer, Bering Sea Water **was** clearly present at the outermost stations of the three most westerly transects. There was evidence of a smaller influence of BSW at some other stations. At the remaining measurement locations where there was sufficient depth for a **lower** layer, Arctic Surface Water occupied the deeper portion of the water column. Even at stations containing a pronounced core of BSW, ASW was found beneath the BSW if the water depth was sufficient (e.g. stations **t2-5** and **t3-5**).

**CHW** was recognized at the outermost stations on transects 1 and 2 (**t1-4**, **t1-5**, ctd 44, ctd 45, **t2-5**). **It was not** prominent on the more easterly transects (3 and 4), although there was weak evidence of the influence of **CHW** at station **t4-5**.

The inner shelf T/S diagrams (Fig. 52) demonstrate a remarkable consistency among the 20-odd **CTD stations** within 20 km of the coast. At all locations, all or most of the T/S curve lies on a line connecting the core ASW characteristics with warm, comparatively saline T/S characteristics (i.e. at **3°C**, salinities of 26-28.5 **psu**). The T/S curves are shifted toward greater salinities for the same temperatures than were observed farther offshore in either 1985 or 1986. Surface temperatures at inner shelf CTD stations in 1985 were **all 1.0°C** or less, much **lower** than the 3.0 to **5.0°C** measured at the eastern inner shelf stations in 1986.

At four of the inner shelf CTD stations (86-1, 86-7, 86-9 and 86-10), the T/S curves revealed **strong** salinity gradients extending to the surface even though the temperature profiles were uniform (ranging from **4.0°C** at station 86-10 to **<1.0°C** at station 86-9). The presence of a strong isothermal **halocline** may indicate freshwater influence from local estuaries, or in the case of the **low** temperatures at station 86-9, local ice melt.

#### Inshore Fine-Scale Oceanographic Features

In 1986, intensive oceanographic observations were collected over the inner **shelf**, particularly in the eastern half of the study area. Inner shelf data consisted of (1) boat-based CTD stations and transects conducted from 4 to 7 September 1986 in areas used by bowhead whales during the same period; (2) aircraft transects flown parallel to and perpendicular to the coast from 5 to 10 September; and (3) satellite imagery of 6, 8 and 10 September, processed

to provide high resolution maps of surface Temperature (Fig. 33). These data are important because physical factors probably affected the abundance and distribution of **zooplankton** and hence bowhead **whales** in the nearshore zone in **1986**. The inner shelf data available for **1985**, while much **less** extensive than **the** 1986 data set, were examined to document differences between **the** two years.

4 September 1986---A detailed aircraft survey was conducted in the coastal area immediately west of Herschel Island, where bowhead **whales** had been observed on 3 September **1986**. Aircraft measurements of surface temperature and **reflectance (R640)** revealed a nearshore band of **turbid water** (equivalent to a secchi depth of <3 m) that was confined to within 2-3 km of the coast off Komakuk, but extended up to **7-8 km** from shore immediately west of Herschel Island (Fig. 53). Even higher turbidities occurred in the very shallow waters of Whaleboat Passage separating Herschel Island from the mainland. This shallow water was **also** very warm, **>4-5°C**.

The boat-based data consisted of five CTD stations, two (stations 86-1 and a) within the turbid nearshore band and three (b, c and 86-2) in waters of progressively reduced turbidity. On the transect of CTD stations between stations a and 86-2, which formed a south-to-north-line perpendicular to the mainland coast, continuous measurements of surface temperature **along** with spot measurements of salinity were collected. The two stations located in the nearshore band of turbid water had a **comparatively** uniform surface layer extending to 4-5 m depth, with comparatively **low** temperatures (**3.5°C**) and salinities (**24.1 to 25.2 psu**). Beneath **an intense, thin pycnocline** extending over only 3 m, a **lower** layer of comparatively warm temperatures (-0.1 to **1.3°C**) and **low** salinities (29.0 to 30.7) was present. At the CTD stations farther from the mainland coast, surface temperatures {3.3 to **4.0°C**) and salinities (25.3 to 26.0) were higher and the upper layer was much shallower. However, beneath the shallow **pycnocline** the water **at** these more offshore locations was **colder** and more saline than **at** the more inshore stations. Thus, the horizontal gradients appeared **to** differ in sign between the surface and **lower** layers. There was **also** evidence in the surface T/S data of **an** abrupt increase in surface temperature, by approximately **0.5 °C**, just north of CTD station b.

The absence of well-mixed conditions in the surface layer at the stations farther offshore suggests that warm, more saline surface water may have been moving past these stations. The aircraft data suggest that the source of the warmer water may have been the Mackenzie Bay water present north of Herschel Island (Fig. 31).

5 September 1986---Initially two CTD stations were occupied on the inner portion of boat transect 4, just east of Demarcation Bay. Then, boat-based operations shifted west to the inshore area off the **Kongakut** River Delta, where feeding bowhead whales had been observed from the aircraft that same day. The '**Annika Marie**' sampled at CTD station **86-5**, 2-3 km from **the** coast at the location with whales, and then **travelled** 11 km offshore. Following two CTD stations (d and 86-6 **separated** by approximately 5 km), the boat headed back inshore toward the initial sampling location (86-5) and completed the day with CTD station e, located about 1 km north of station **86-5**. Continuous surface temperature data were not available due to instrument problems. The aircraft **also** flew special transects on 5 September, including two tracks within a few

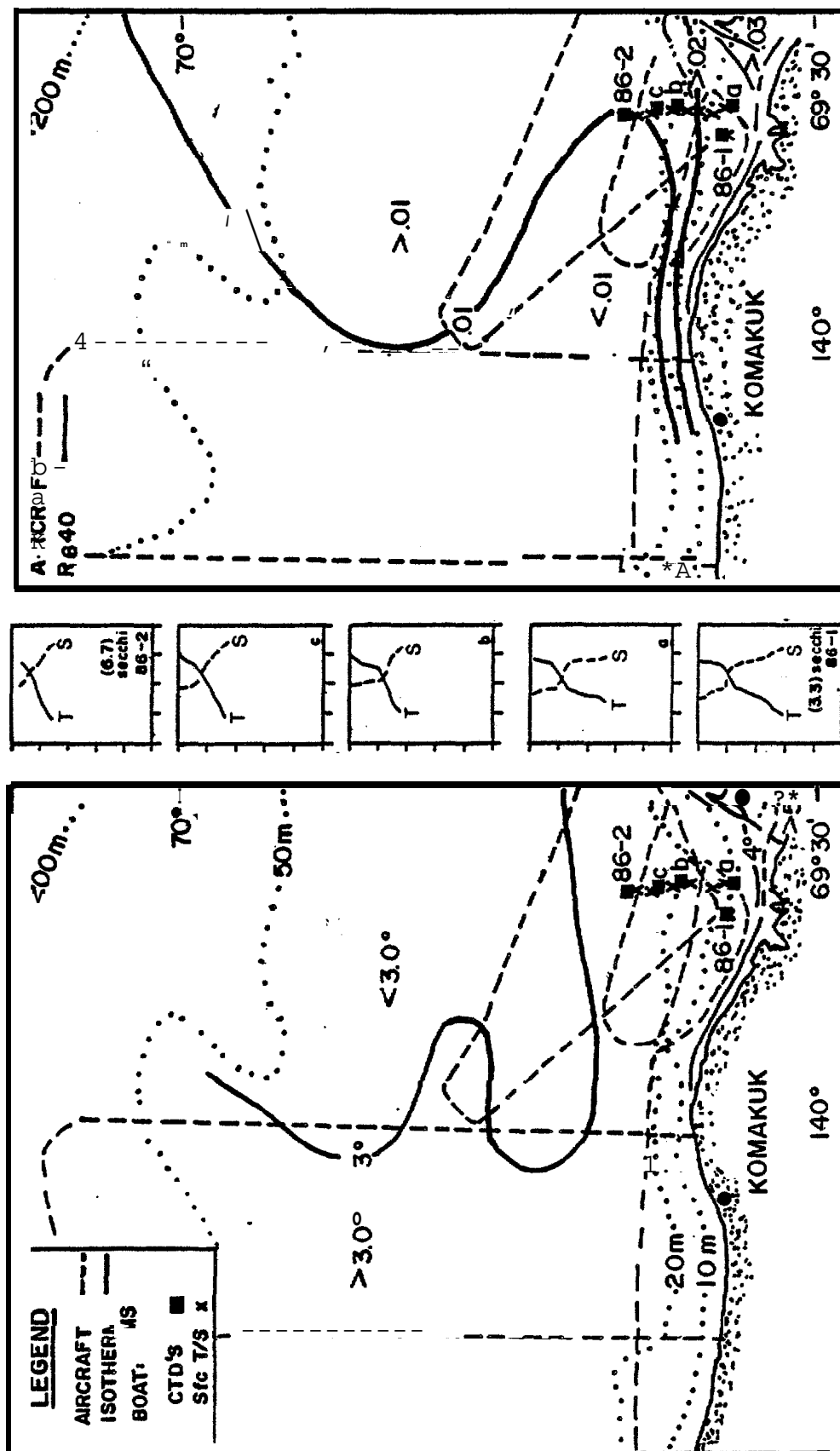


FIGURE 53. A summary display of oceanographic measurements collected on 4 September 1986 over the inner shelf region between Herschel Island and the eastern boundary of the study area.



kilometers of and parallel to the coast, and three transects perpendicular to shore over or near the **Kongakut** Delta area.

Mapping of the combined aircraft and boat-based data (Fig. 54) reveals two prominent oceanographic features:

1. A narrow nearshore band of **turbid** water (inferred secchi depth  $<3$  m) **along** the barrier island; the width of this band ranged from one to several km. The nearshore band appeared to intensify immediately to the west of Demarcation Bay, and it was apparently present at station 86-3 just to the **east** of Demarcation Bay, as indicated by the **low** secchi depth reading of 1.8 m.
2. A broad expanse of warm and comparatively clear water offshore of the turbid nearshore band off the **Kongakut** Delta. The aircraft data revealed temperatures exceeding  $4.0^{\circ}\text{C}$  as far as 25 km from shore. Satellite data obtained 1 day later, on 6 September (Fig. 33A), indicated that the highest temperatures ( $>4.2^{\circ}\text{C}$ ) within the study area were off the **Kongakut** Delta.

The nearshore band of turbid water was also characterized by **lower** surface temperatures, and surface salinities comparable to or lower than those farther offshore. Lower temperatures are indicated from the aircraft data, where the two flights parallel to the coast revealed temperatures of  $2.3$  to  $3.2^{\circ}\text{C}$ . From CTD data obtained at station 86-5 located only 2.5 km from the barrier island a surface temperature of  $3.6^{\circ}\text{C}$  was measured. (Note that nearshore CTD stations 86-5 and e are farther offshore than the core of the nearshore band. The width of the band was particularly narrow at this location. The surface temperatures at those stations were greater than some of those measured from the aircraft. Similarly, the secchi depth at station 86-5 was 6.1 m; this is equivalent to an R640 reading of approximately 0.01, which is lower than R640 values found close to shore.)

Comparison of CTD station pairs (86-5 vs. 86-6, e vs. d; Fig. 54) provides insights into subsurface conditions near the edge of the nearshore band, where bowheads were, feeding, and well offshore, within the **warm** inner shelf waters. Both nearshore stations (86-5, e) exhibited a more intense **pycnocline**, along with considerably **lower** temperatures and higher salinities within the **pycnocline** and in the **lower** layer. The differences amounted to  $1\text{--}2^{\circ}\text{C}$  and 2-4 **psu** and were **largest** over depths of 7 to 15 m. These CTD comparisons suggest that the subsurface waters had more pronounced Arctic **Water** characteristics in the nearshore zone than was the case farther offshore in the adjoining warm inner shelf waters.

6-7 September 1986.--On 6 September, intensive measurements were obtained from **the boat and** aircraft off the **Kongakut** Delta, overlapping the study area of the previous day but extending farther east.

The aircraft-based turbidity measurements (Fig. 55) indicated that the turbid nearshore band had increased in width by 6 **September**, extending some 5-11 km beyond the barrier islands. On the previous day, this band had extended as little as 1 km from the barrier island. Based on the combined boat, aircraft and satellite (Fig. 33A) data, the broad area of warm water over the inner **shelf** continued to extend at least 25-30 km off the **Kongakut**



FIGURE 54. Distribution of inferred turbidity levels (**R640** index) and temperature over the inner shelf, as mapped from aircraft and boat on 5 September 1986. **Also** shown are vertical profiles of temperature and salinity at two locations where whales had been observed ('whales') and at two nearby locations without **whales** ('control').

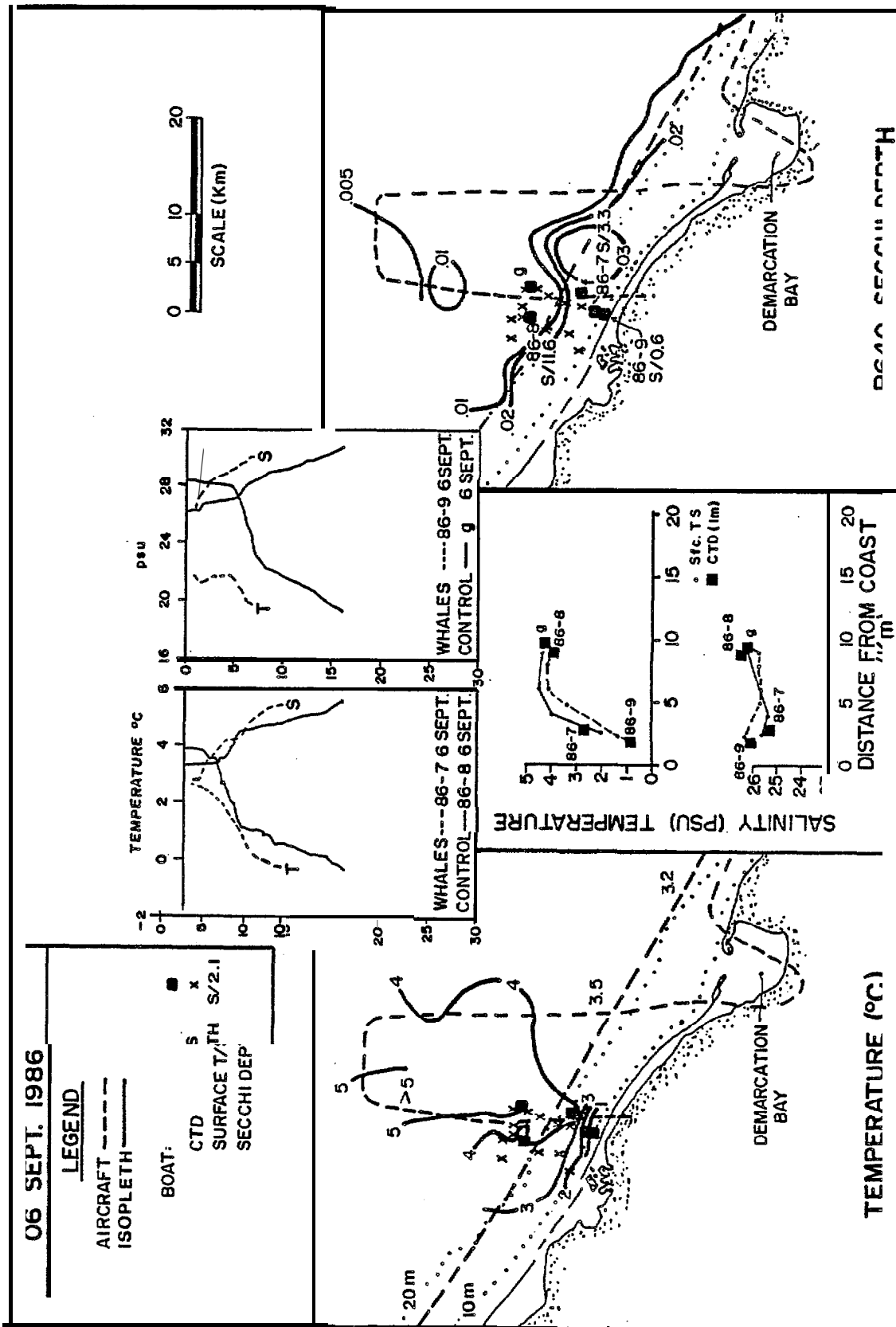


FIGURE 55. Distribution of inferred turbidity levels (R640 index) and temperature over the inner shelf, as mapped from aircraft and boat on 6 September 1986. Also shown are vertical profiles of temperature and salinity at two locations where whales were observed ('whales') and at two nearby locations without whales ('control')

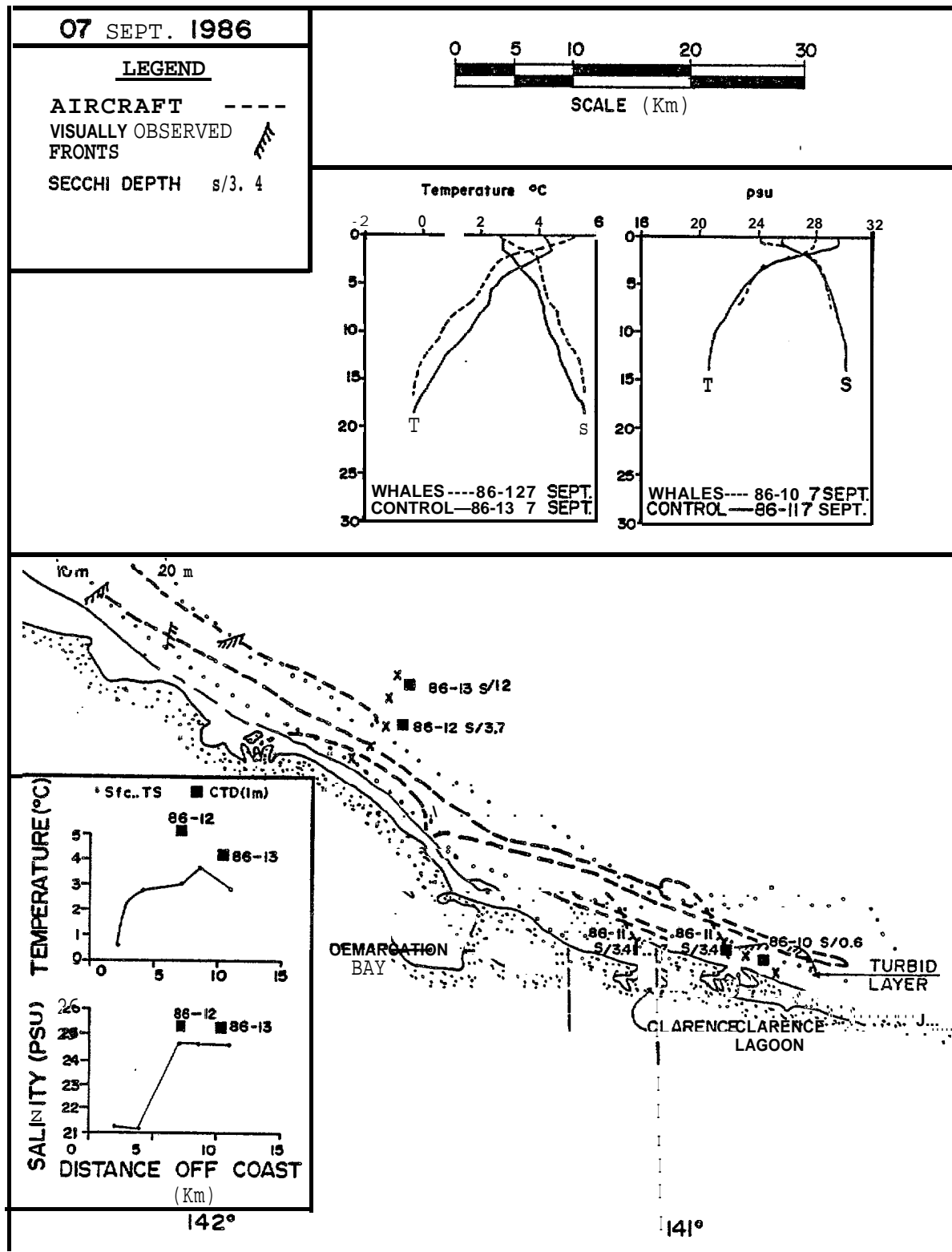
Delta. Within the turbid nearshore band, surface temperatures were again lower than those farther offshore. Now, however, an intense temperature front occurred approximately midway through the nearshore band. At this location, 2-3 km from the barrier island, temperatures changed abruptly from over 4°C on the offshore side to **1-2°C** closer to shore. This cold water along the barrier islands **likely** resulted from melting of sea-ice grounded west of the **Delta**; however, the salinity remained unchanged at the sites of low temperature measurements. Indeed, surface salinities exhibited very **little** change from 2 to 10 km off the coast, ranging from 25.3 to 26.3 psu (Fig. 55).

CTD profile data were collected at sites 86-9 (within 2 km of the coast), 86-7 (about 3 km offshore) and 86-8 and g (**9-10 km** offshore and **well** outside **the** turbid nearshore band). At **the** two innermost stations **within** the nearshore **band**, **the pycnocline** extended to within 2 m of the surface. **Beneath the** intense but shallow **pycnocline**, temperatures were cooler (by 1-5 Co) and salinities greater (by 1-3 **psu**) than those measured farther offshore at **the** same depths of 3-10 m. As on the previous day, Arctic Water characteristics were much more pronounced at depth within the nearshore band, where **whales** were feeding, than in the warm inner shelf waters farther offshore.

On 7 September 1986 the turbid nearshore band still extended offshore to distances comparable to those of the previous day (Fig. 56 vs. 55). From the aircraft, prominent turbidity **fronts** were observed visually **along** the edge of **the** nearshore band. Boat-based measurements were carried out along an onshore-offshore transect 4 km east of **the** easternmost boat transect of the previous day. **On** this transect, surface temperatures and salinities were somewhat lower than those farther west on 6 September. **Up to** 10 km from shore, surface temperatures and salinities were 1 C° and 1 psu lower. Very **low** temperatures (**<1°C**) were again measured within 1 **km** of the barrier island. On 7 September, unlike **the** 6th, salinities decreased **sharply** from 24.6 psu offshore to 21.5 or less near the island. Bands of ice were present along the **island** on this transect, accounting for the reduced temperature and salinity.

Two **CTD** profiles 'taken on 7 September, at stations 86-12 near the edge of the nearshore band and 86-13 well beyond it, again indicated temperature and salinity differences at depth. As on the previous two days, the innermost CTD station had a shallow, **intense pycnocline**, **below** which waters were about 1 Co **cooler** and salinities 1 psu greater than those outside the nearshore band. The differences extended over most of the water column, **from** 3-4 m to 17 m. Whales again fed in the colder water close to shore, i.e. at station **86-12**.

Additional boat and aircraft data were collected off Clarence Lagoon just east of the official study area on 7 September. Bowhead whales had been observed there on the previous day. A visually prominent and wedge-shaped turbid nearshore band extended nearly 4 km offshore east of the lagoon, but was reduced in width to 2 km off the entrance of the lagoon and was absent altogether farther **west**. CTD profiles were collected at site **86-10**, within **the** turbid band (**secchi** depth of only 0.6 m), and at site 86-11 a similar distance from shore just west of the turbid water (**secchi** depth of 3.4 m). A very thin surface layer was present at both stations, extending **only** 1-2 m **below** sea level. Within the turbid nearshore band, both the surface temperature and surface salinity were lower than the values measured farther west at the edge of the band. However, beneath the surface layer, the vertical profiles were virtually identical.



**FIGURE 56.** Distribution of inferred turbidity levels (R640 index) and Temperature over the inner shelf, as mapped from aircraft and boat on 7 September 1986. Also shown are vertical profiles of temperature and salinity at two locations where whales were observed ('whales') and at two nearby locations without whales ('control').

10 September 1986.--Extensive aircraft-based measurements were collected, **along** with boat-based sampling along the easternmost broad-scale boat transect (no. 4). Whales were feeding about 6 km NNW of the entrance to Demarcation Bay on this date; they were about 5 km west of boat transect 4. Instrument problems were encountered with **all** aircraft-derived temperature data obtained **>10** km west of Demarcation Bay. **The** aircraft data obtained north of Demarcation Bay were usable, although comparisons with the concurrent boat-based measurements on transect 4 indicate that the aircraft measurements were consistently **low** by approximately **1.3°C**, and they were adjusted upward accordingly. Fortunately, a high resolution satellite image was also available for this same **date** (Fig. 33C). Interestingly, it too required an upward correction of the same magnitude for consistency with the boat-based data (see 'Methods', p. 38).

The combined data showed that the nearshore band of turbid water was again present along the barrier islands (Fig. 57). West of longitude **141.7°W**, it extended 3-5 km offshore, as on 6-7 September. However, at longitudes 141.4 to 141.7° w, turbid water extended 30-35 km offshore. This turbid feature occurred as broad filament oriented due north, with an apparent width of 5 km or more. From the **large** scale patterns of surface turbidity and water color observed from the aircraft, the turbid offshore waters appeared to be an extension of high nearshore **turbidities**, being advected northwestward from the coast near Demarcation Bay. Water color was not uniform within the offshore area of high turbidity, but had a banded appearance. Surface temperatures within this broad band of turbid water were estimated as **4.0-4.5°C** from the aircraft measurements. The high resolution satellite data for this same date (Fig. 33C) also show this feature as a narrow (5-8 km) band of warmer surface **water (>4.0°C)** extending over 30 km from shore off Demarcation Bay, and continuing to the northwest, with temperatures exceeding 4°C some 30 km north of the **Kongakut** Delta.

On this same day, **well** defined eddy patterns outside the high turbidity waters were observed and photographed from the aircraft. These features were evident as alternating bands of different water colors in a circular formation. The bands **spiralled** inward to the center of the pattern, suggestive of a small **cyclonic** eddy with surface convergence occurring at its center. Boat-based sampling at the surface through one of the eddies (north of station **t4-3**) was inconclusive due to the **large** station separation} although the salinity may have increased somewhat. Along boat transect 4, **low** surface salinities were measured just off the coast, followed by markedly increasing surface salinities to maximum levels of 27.8 psu approximately 6 km offshore. Surface temperatures were relatively uniform over this same portion of the transect. CTD profiles were obtained at stations **t4-1** and **t4-2**, located 1.5 and 6.5 km respectively from the coastline. Although temperatures at the surface were warmer nearer the coast, temperatures beneath the **pycnocline** were lower by about 1 Co near the coast. As at the pairs of CTD stations studied on 5-7 September, cold, saline Arctic Water was more prominent at the **nearshore** station than farther from shore.

Thus, there was a recurring pattern for Arctic Water characteristics to be better developed within the nearshore zone than at the nearest adjacent inner **shelf** station. This is illustrated in the vertical sections of Figures 58 and 59. For all pairs of nearshore-inner shelf stations sampled on 5-10 September 1986, temperature and salinity **isopleths** were tilted upward toward

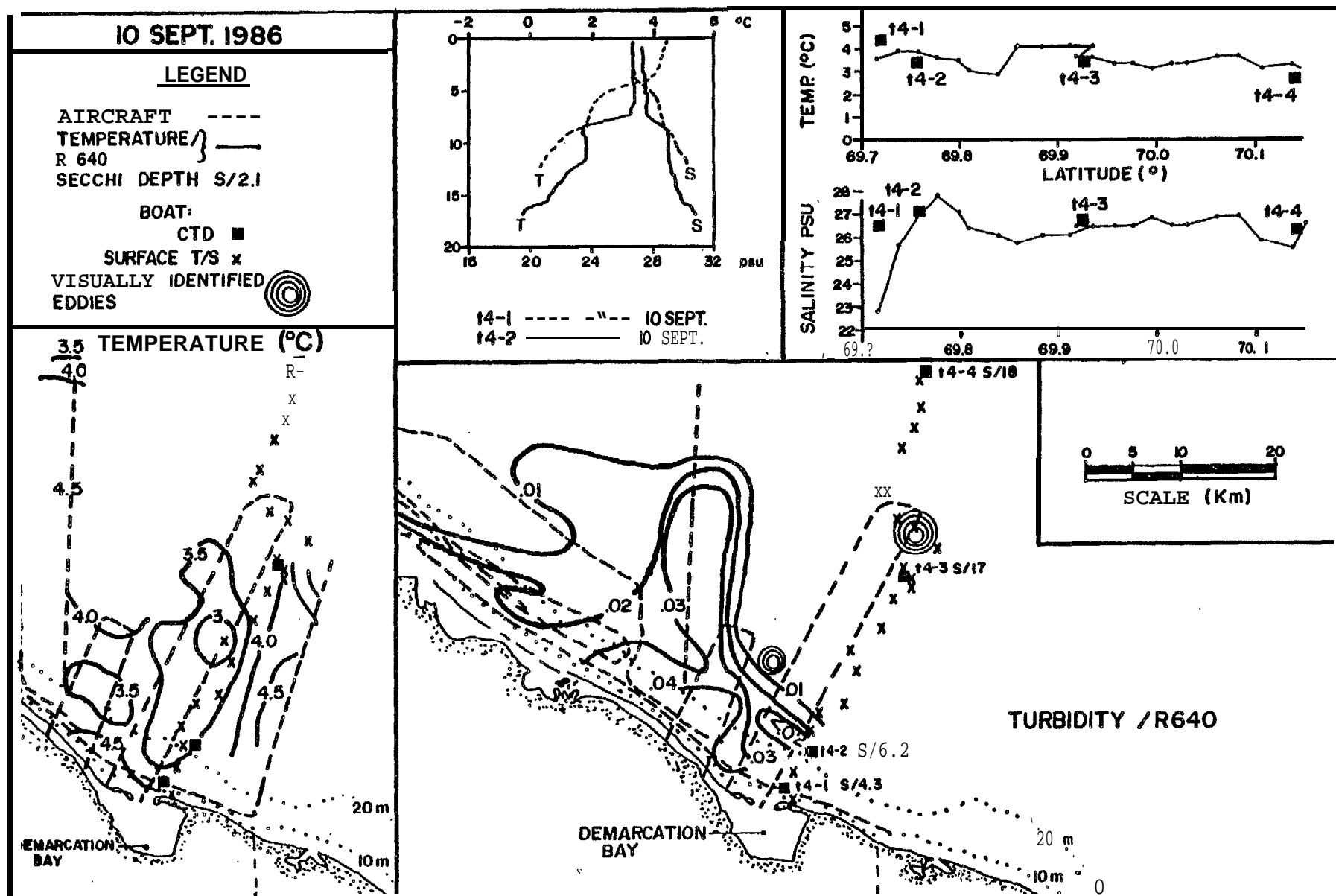


FIGURE 57. Distribution of inferred turbidity levels (R640 index) and temperature over the inner shelf, as mapped from aircraft- and boat-based measurements on 10 September 1986.

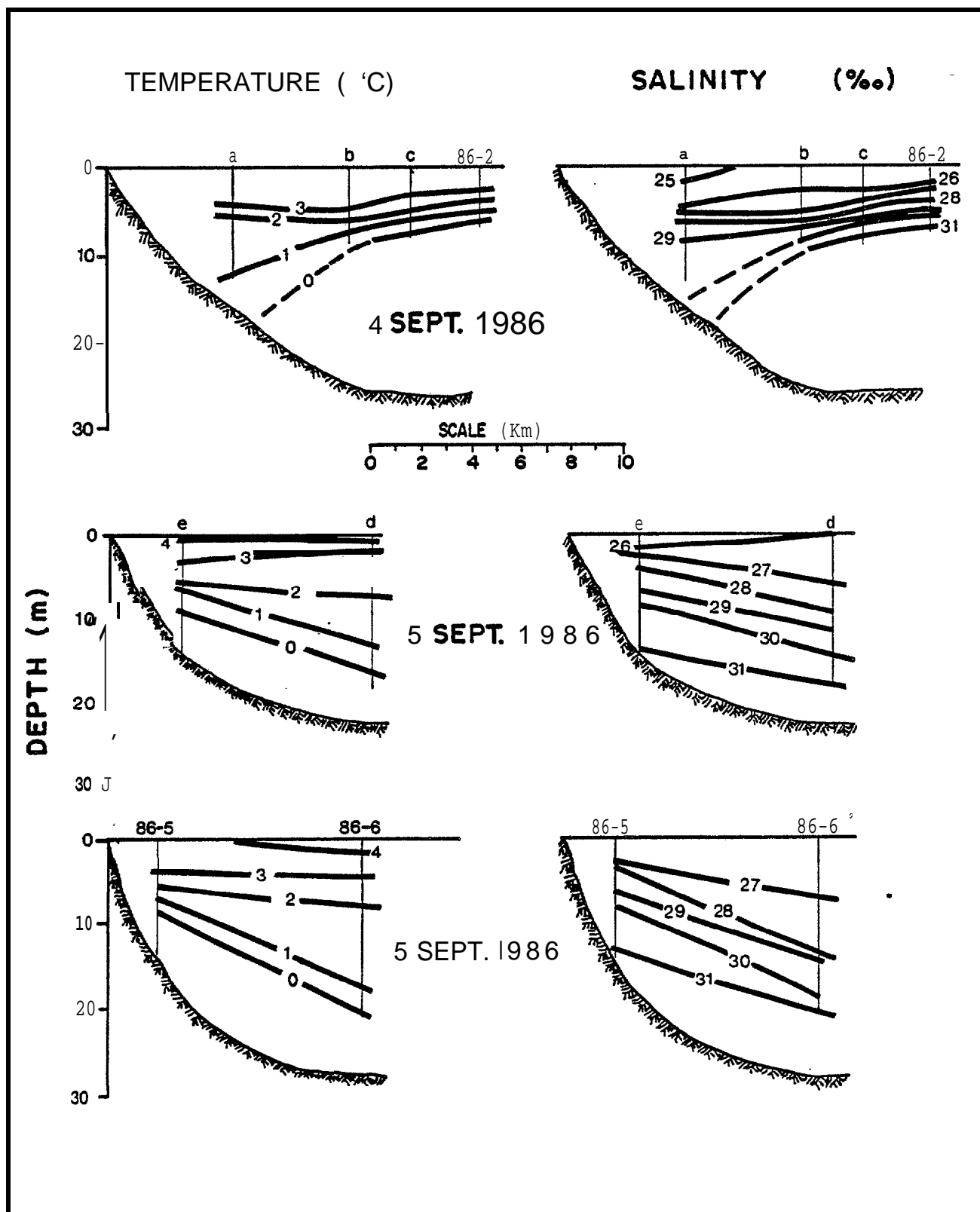


FIGURE 58. Vertical cross-sections of temperature and salinity on transects perpendicular to shore over the inner shelf region, 4 and 5 September 1986.



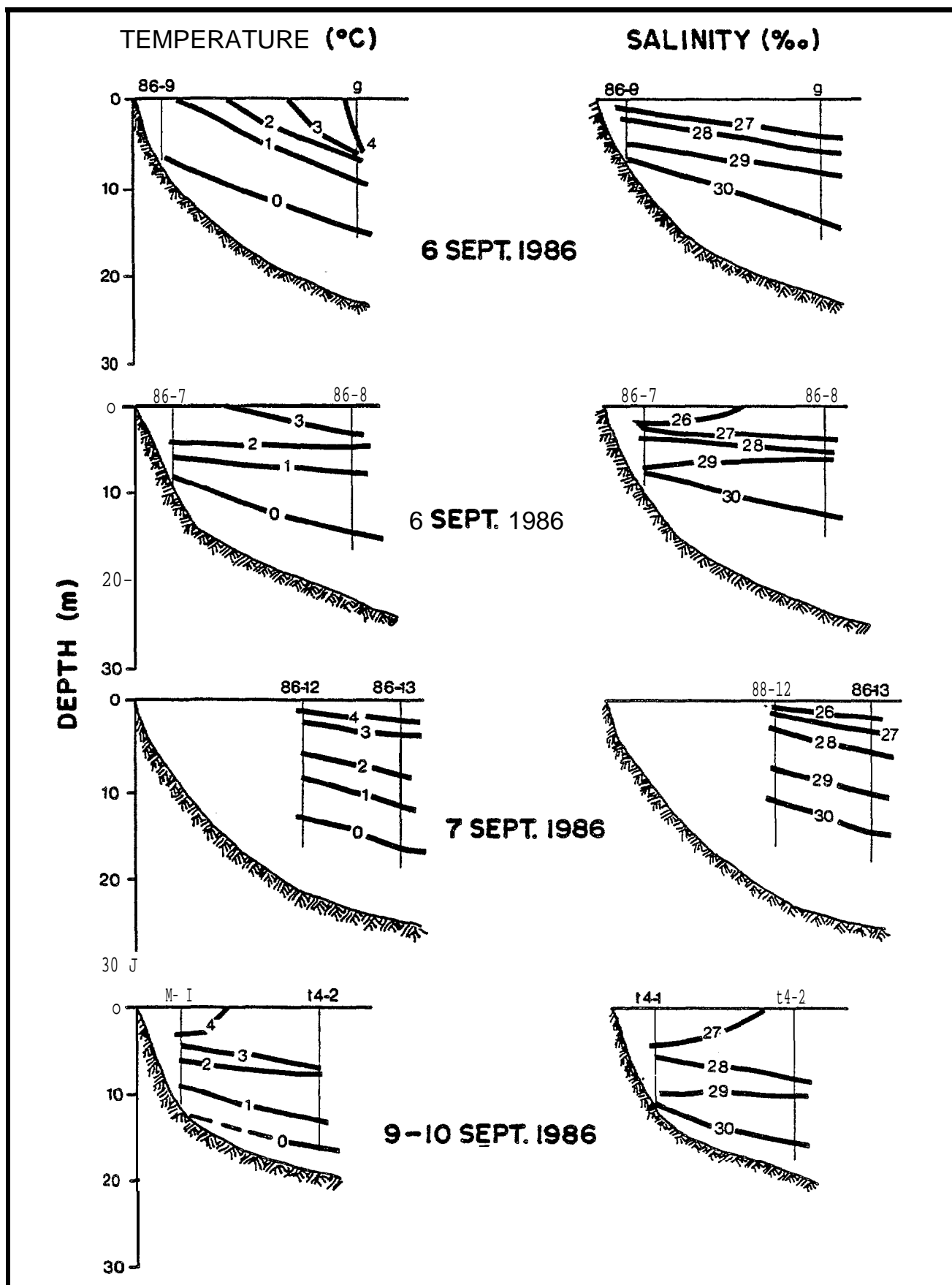


FIGURE 59. Vertical cross-sections of temperature and salinity on transects perpendicular to shore over the inner shelf region, 6, 7 and 9-10 September 1986.

the coast. Thus, intense horizontal gradients were present at depths ranging from a few meters to 15 m. Convergent flow patterns may have been associated with the implied intense subsurface frontal features.

### Frontal Characteristics

Boat-based measurements of surface Temperature and salinity (Fig. 60, 61) showed that changes in surface water properties were **not** evenly distributed over the continental **shelf**. Instead, there were comparatively **large** gradients, or fronts, over distances ranging from **<2** km up to **10** km. Between these fronts, the horizontal gradients were **much** weaker, reduced by as **much** as an order of magnitude (Fig. 62-64). Strong gradients were **also** apparent **in the** airborne radiometer data (Fig. 23, 25, 29, 34, 65) and in **thermal** imagery from satellites, particularly **the** high resolution data for 6, 8 and 10 September 1986 (Fig. 33).

The horizontal **gradients** with the **largest** amplitudes occurred over short distances, typically 200 m to 2 km (Fig. 62-65). These intense fronts were **often** accompanied by a nearby gradient of opposite sign, **e.g.** events II/III on Fig. 62; radiometer data 25-30 km from shore on boat transect 2, Fig. 65; data of 10 and 12 September 1986, Fig. 64. This pattern of pairwise occurrence of fronts having opposite sign is indicative of small scale eddy features, with approximate scale sizes of **<2** to **10** km. Due to the **small** scale size, these eddies were not adequately represented in two dimensions on maps of surface water properties as measured by airborne transects spaced several kilometers apart or on satellite images having 1-2 km resolution.

The surface temperature and salinity data did not always change in "parallel fashion along boat transects (Fig. 62-64). Thus, discussions of surface oceanographic features derived **solely** from thermal data **should** be used with caution. To examine this more closely, the boat-based surface T/S data from 1985 and 1986 were used to examine frontal features represented by temperature changes of at least **0.5°C** and salinity changes of at least **1 psu**. The comparative amplitudes of frontal features defined in this way were examined separately for 1985 boat transects 1 and 2 (Fig. 66) and for 1986 boat transects 1 to 4 (Fig. 67, 68). Along transect 1 in 1985, changes in temperature and salinity were reasonably consistent. The **only** obvious inconsistencies were event 11 on the inner shelf, where the temperature gradient was very strong but the salinity gradient was not (Fig. 66A); and the northernmost 12 km of transect 1, near the **shelf** edge, where temperature continued to increase in the absence of a salinity gradient (Fig. 62A). However, along transect 2 in 1985, much larger discrepancies were evident (Fig. 62B, 66B).

The 1986 boat transect data (Fig. 67, 68) indicate a similar lack of correspondence in some temperature and salinity gradients. This was especially evident along boat transect 3 and the inner portion of transect 4 (Fig. 64), where the match between temperature and salinity gradients was poor. On transect 2, **large** temperature and salinity gradients generally coincided with one another, particularly over **the inner- and outermost** portions of the transect (Fig. 63, 67).

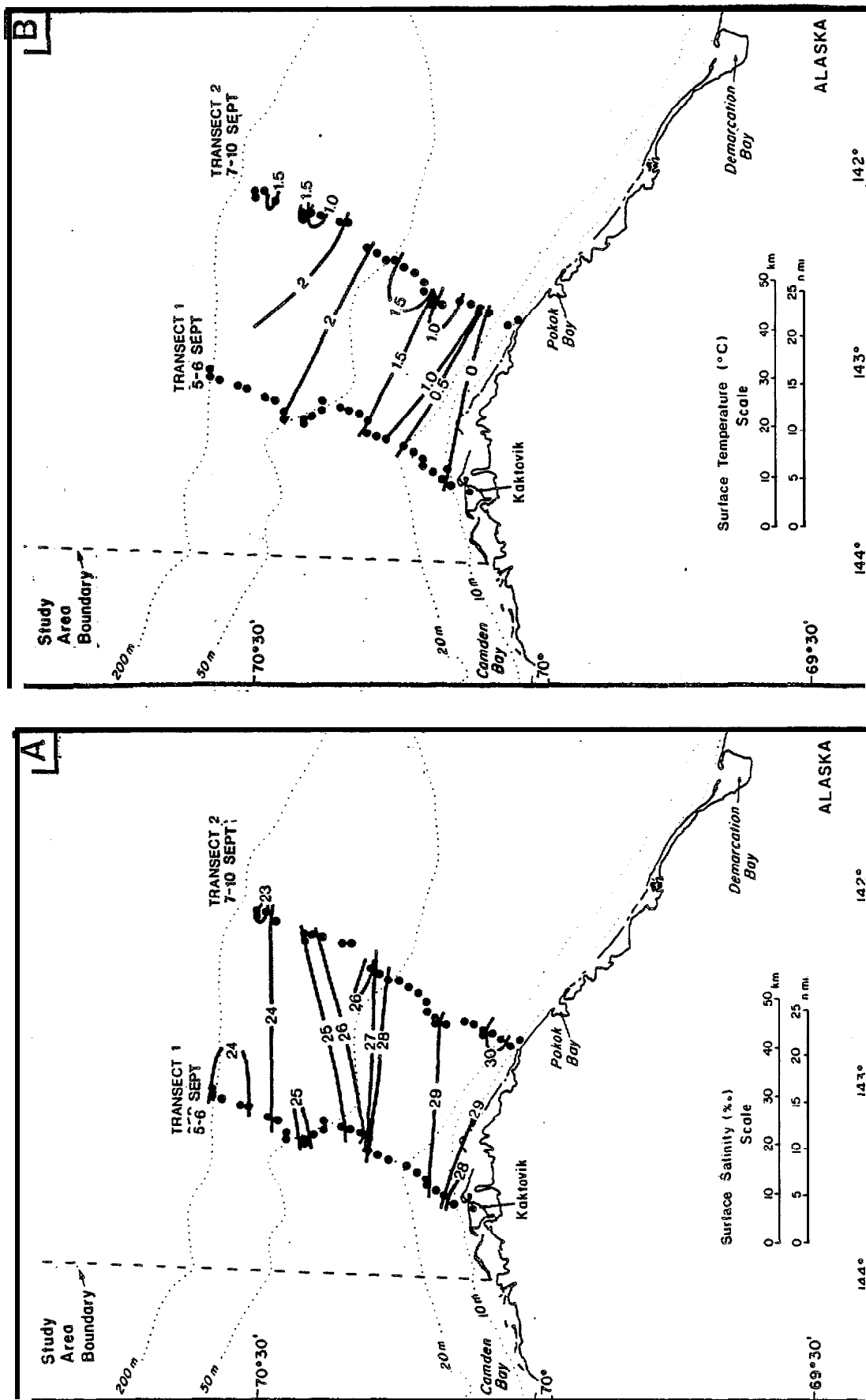


FIGURE 60. The distribution of surface water properties from 5 to 10 September 1985, as inferred from the boat-based oceanographic sampling: (A) salinity and (B) temperature.

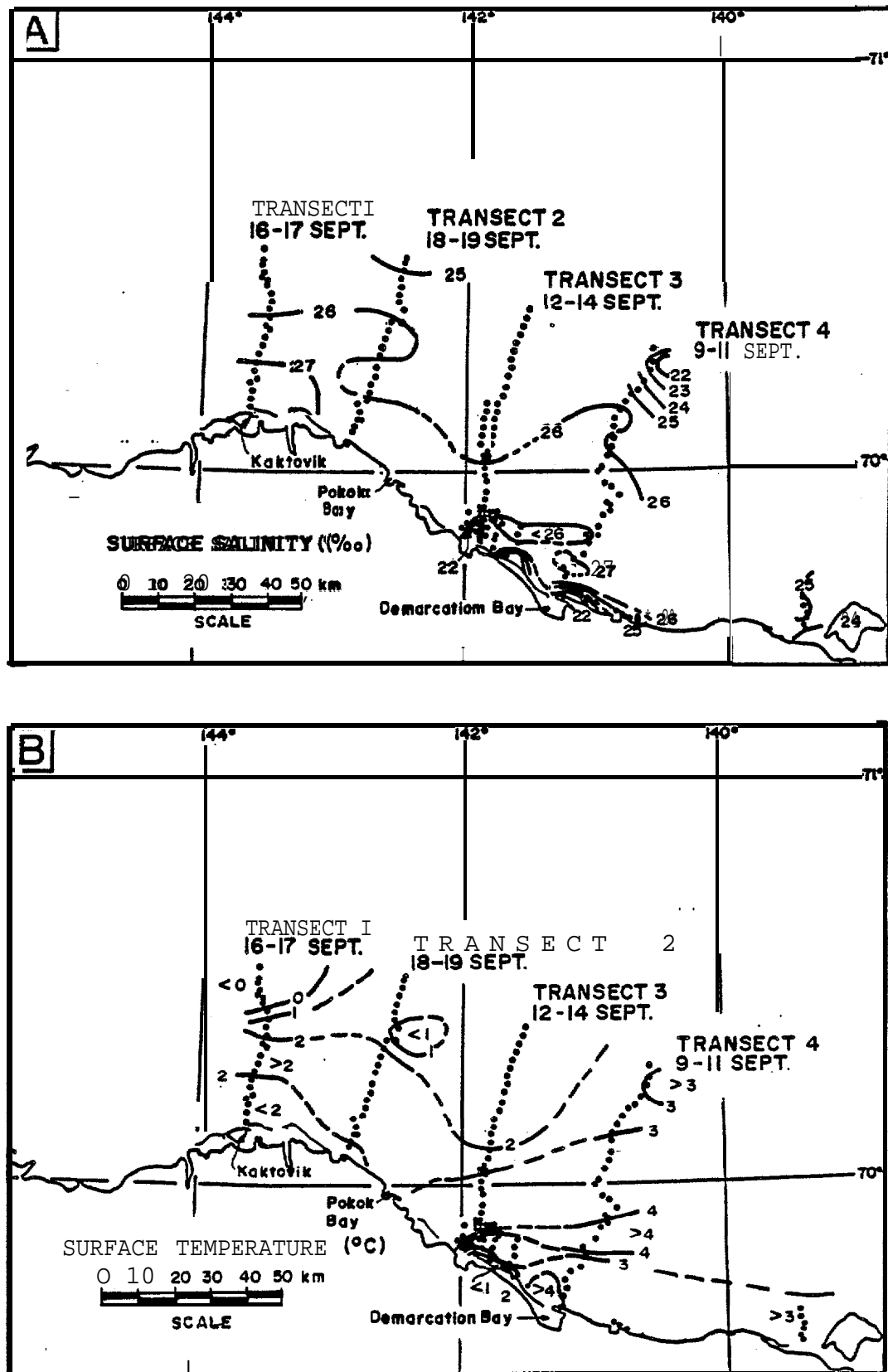


FIGURE 61. The distribution of surface water properties from 5 to 19 September 1986, as inferred from the boat-based oceanographic sampling: (A) salinity and (B) temperature.

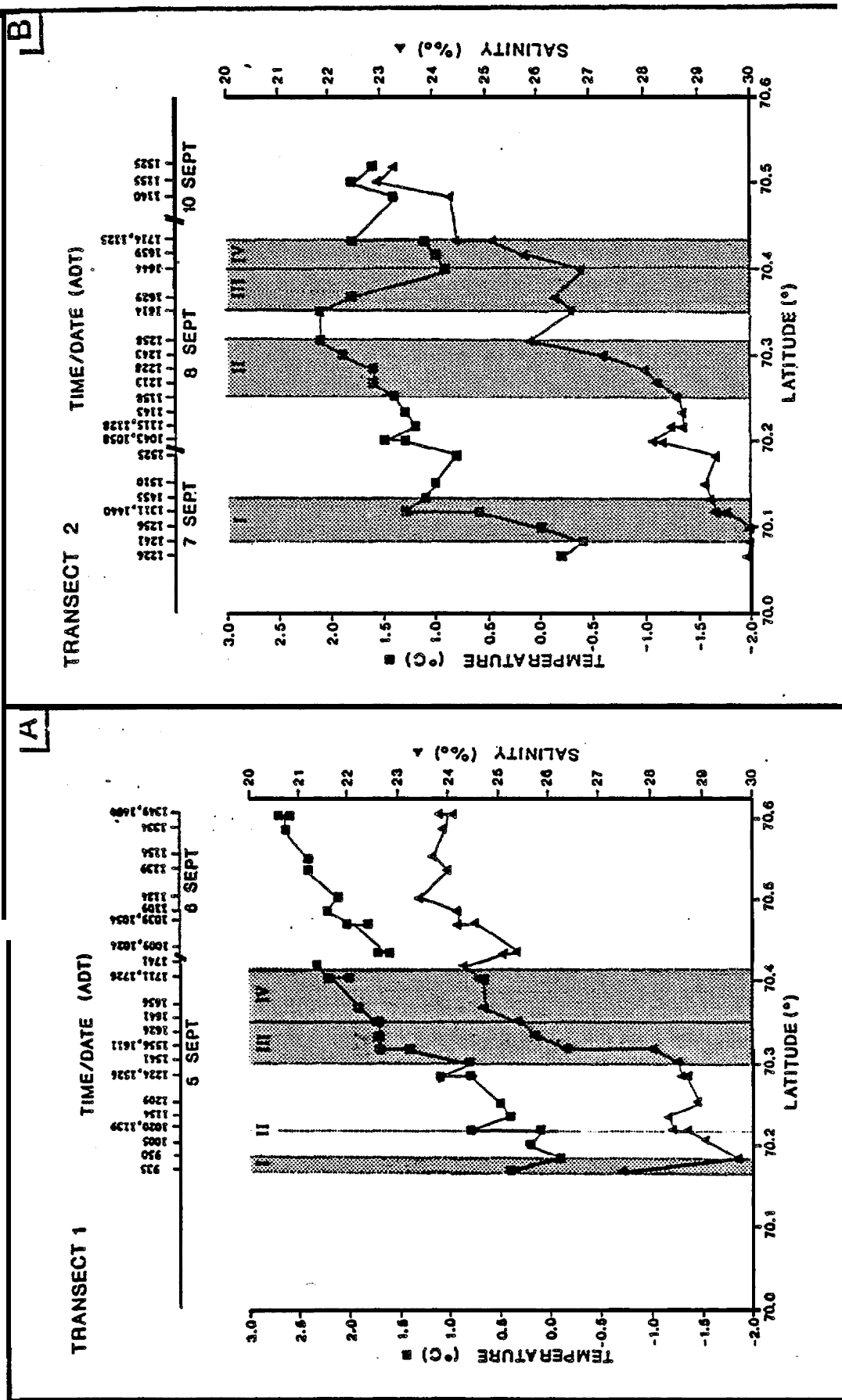


FIGURE 62. The variation of surface temperature and salinity with latitude in 1985: (A) boat transect 1, and (B) boat transect 2. The shaded areas and Roman numerals denote large gradients in temperature and/or salinity.

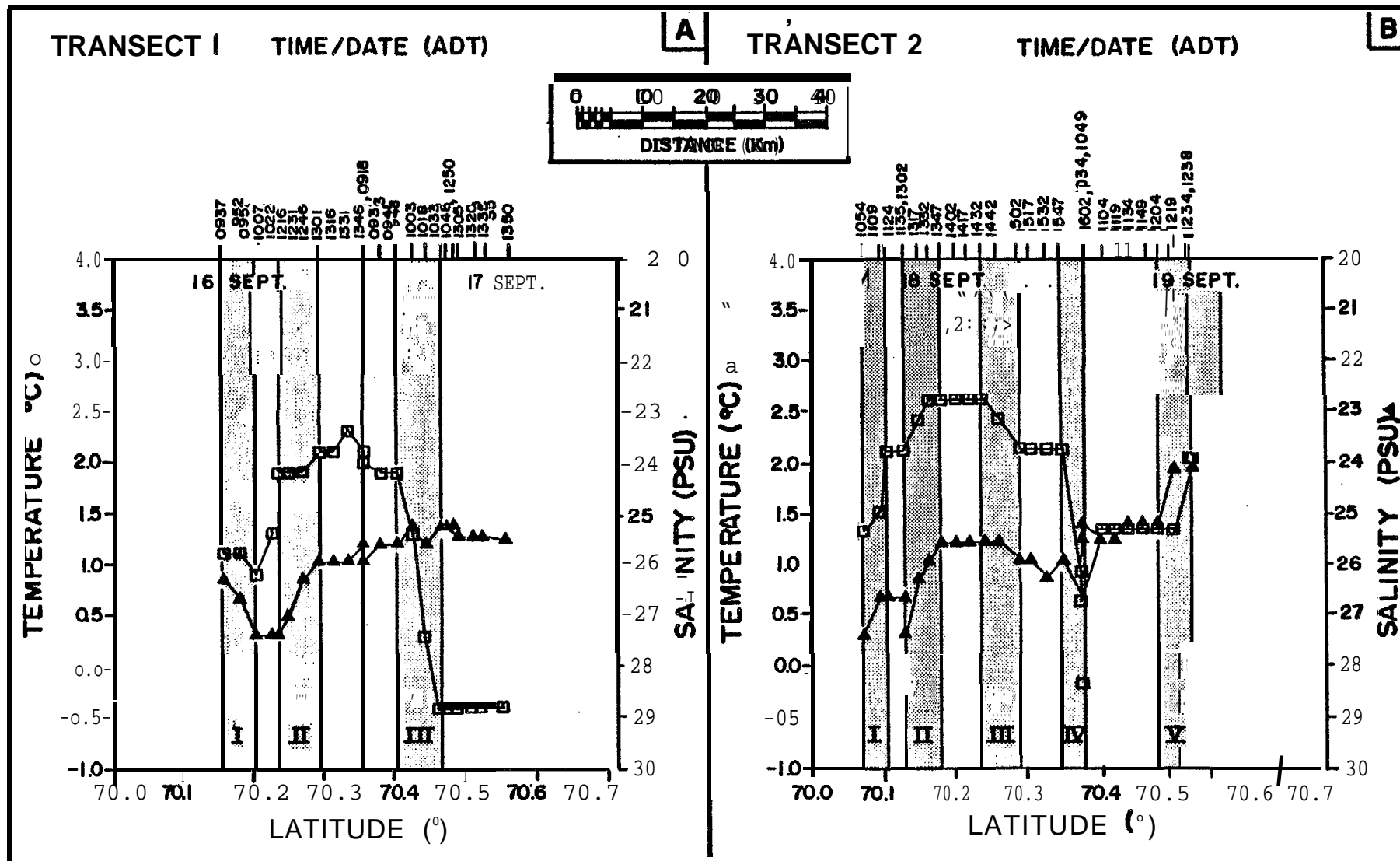


FIGURE 63. The variation of surface temperature and salinity with latitude in 1986: (A) boat transect 1, and (B) boat transect 2. The shaded areas and Roman numerals denote large gradients in temperature and/or salinity.

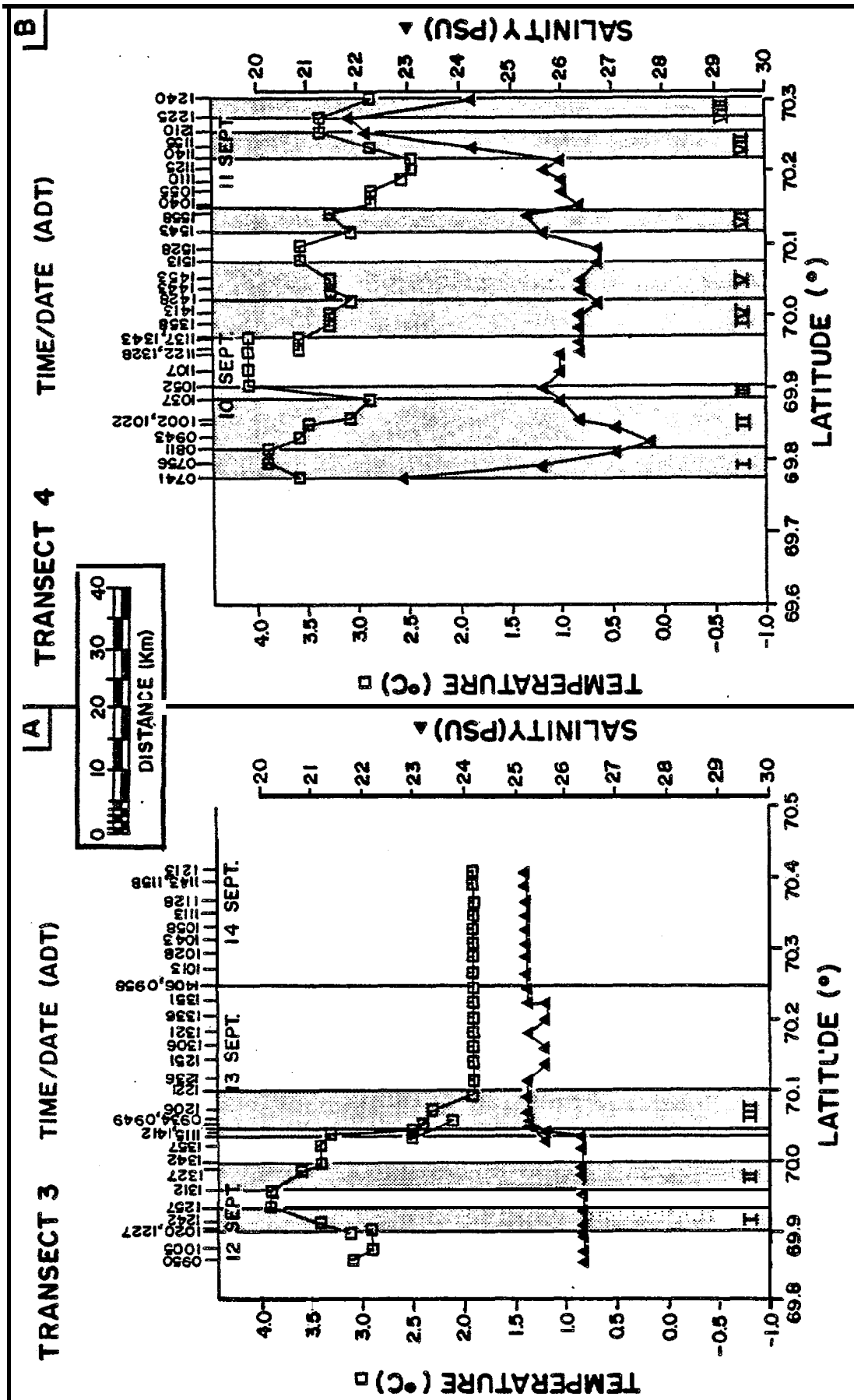


FIGURE 64. The variation of surface temperature and salinity with latitude in 1986: (A) boat transect 3, and (B) boat transect 4. The shaded areas and Roman numerals denote large gradients in temperature and/or salinity.

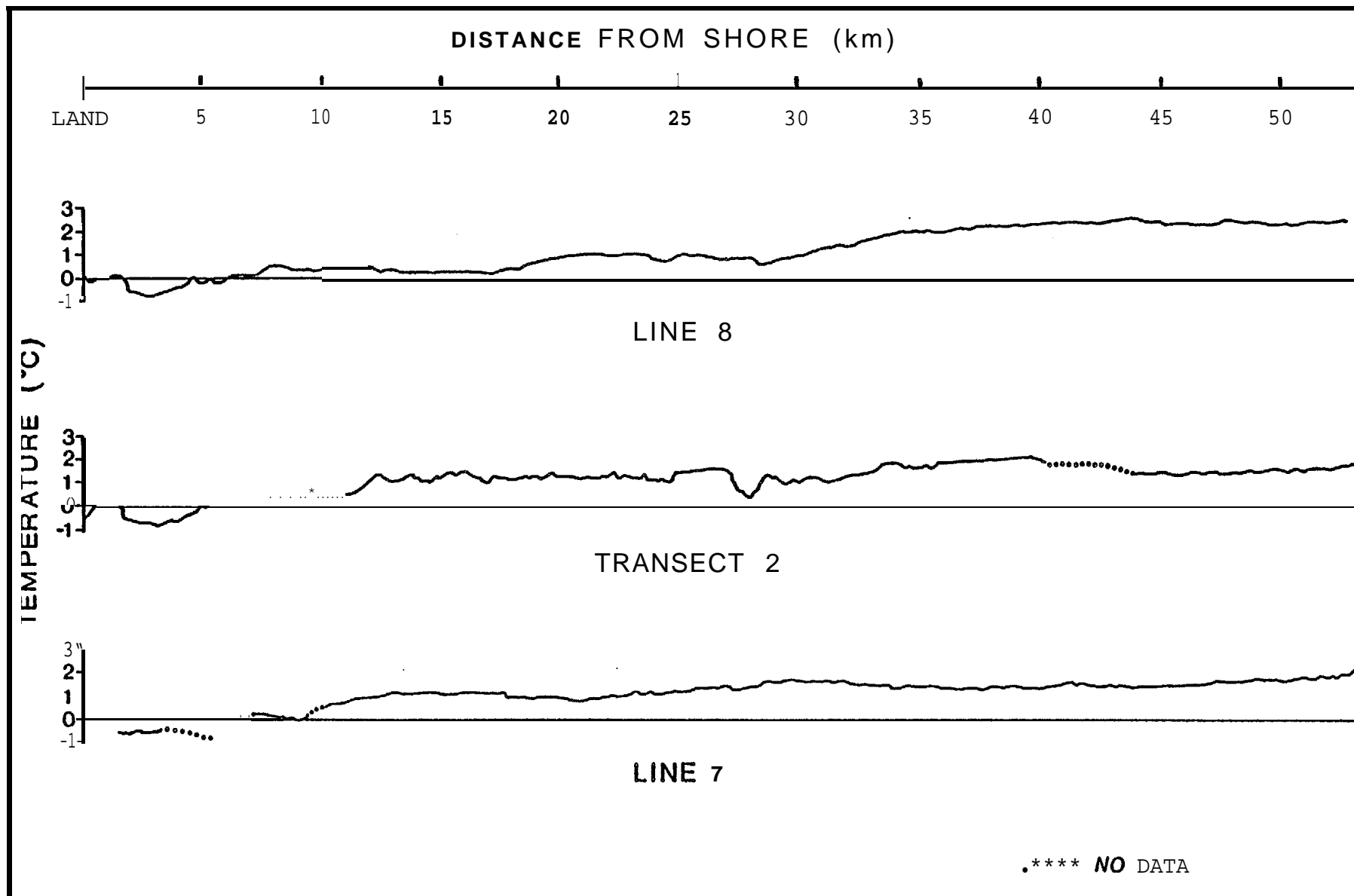
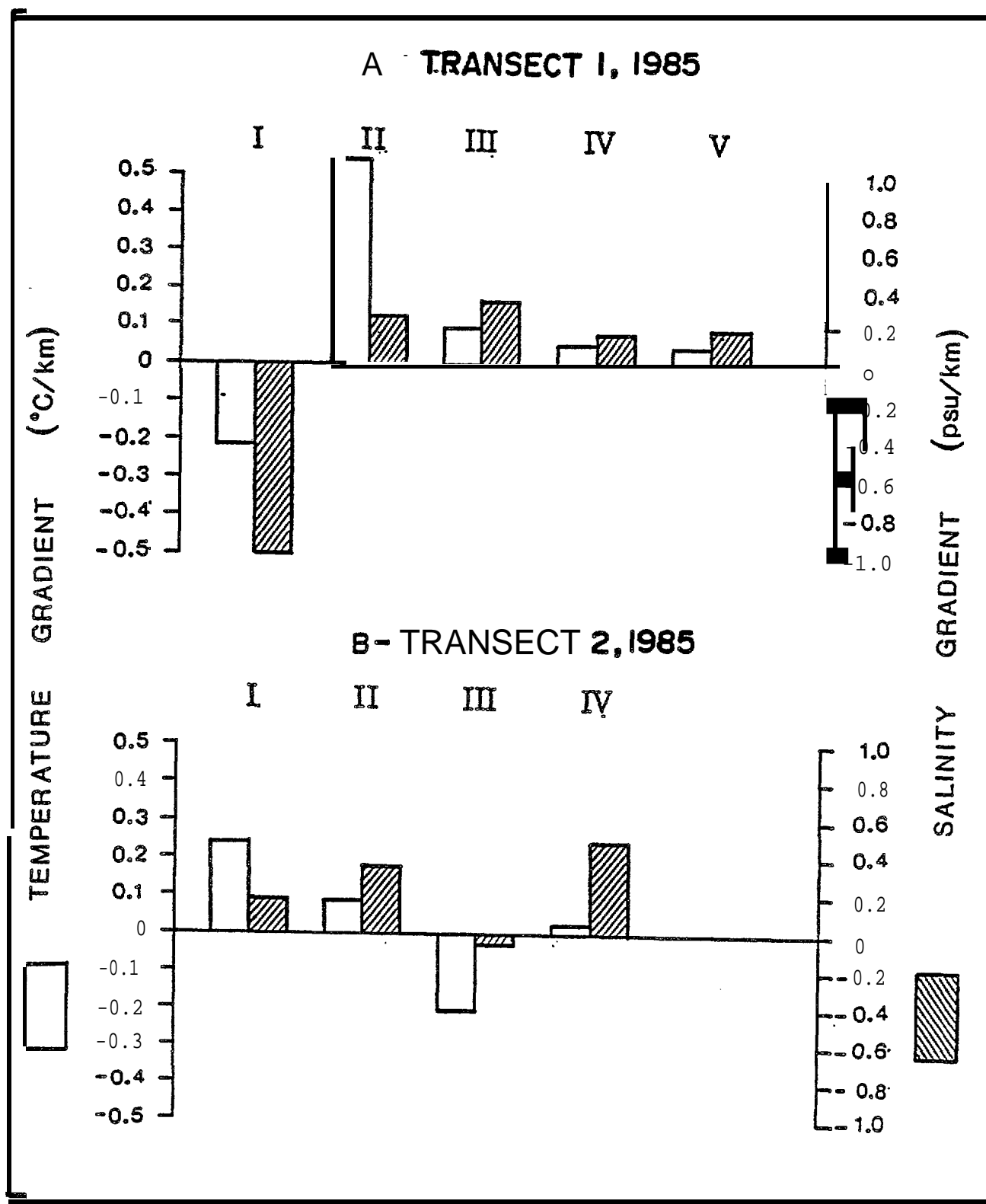
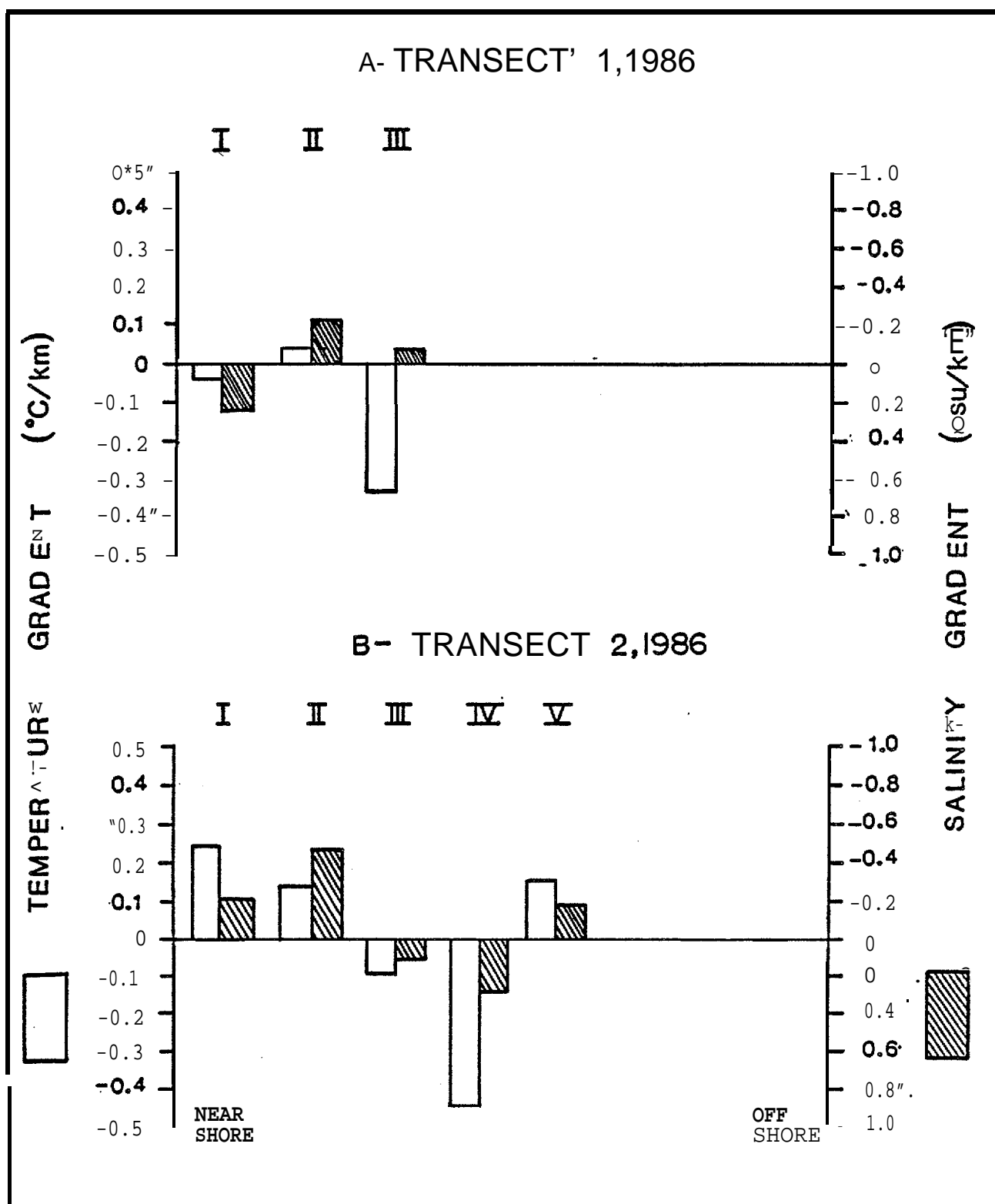


FIGURE 65. The variation of surface temperature **with** distance along airborne remote sensing **lines** 7 and 8 and along boat transect 2, 6 September 1985. Lines 7 and 8 were on opposite sides of transect 2. All measurements were obtained with the Airborne Radiation Thermometer.

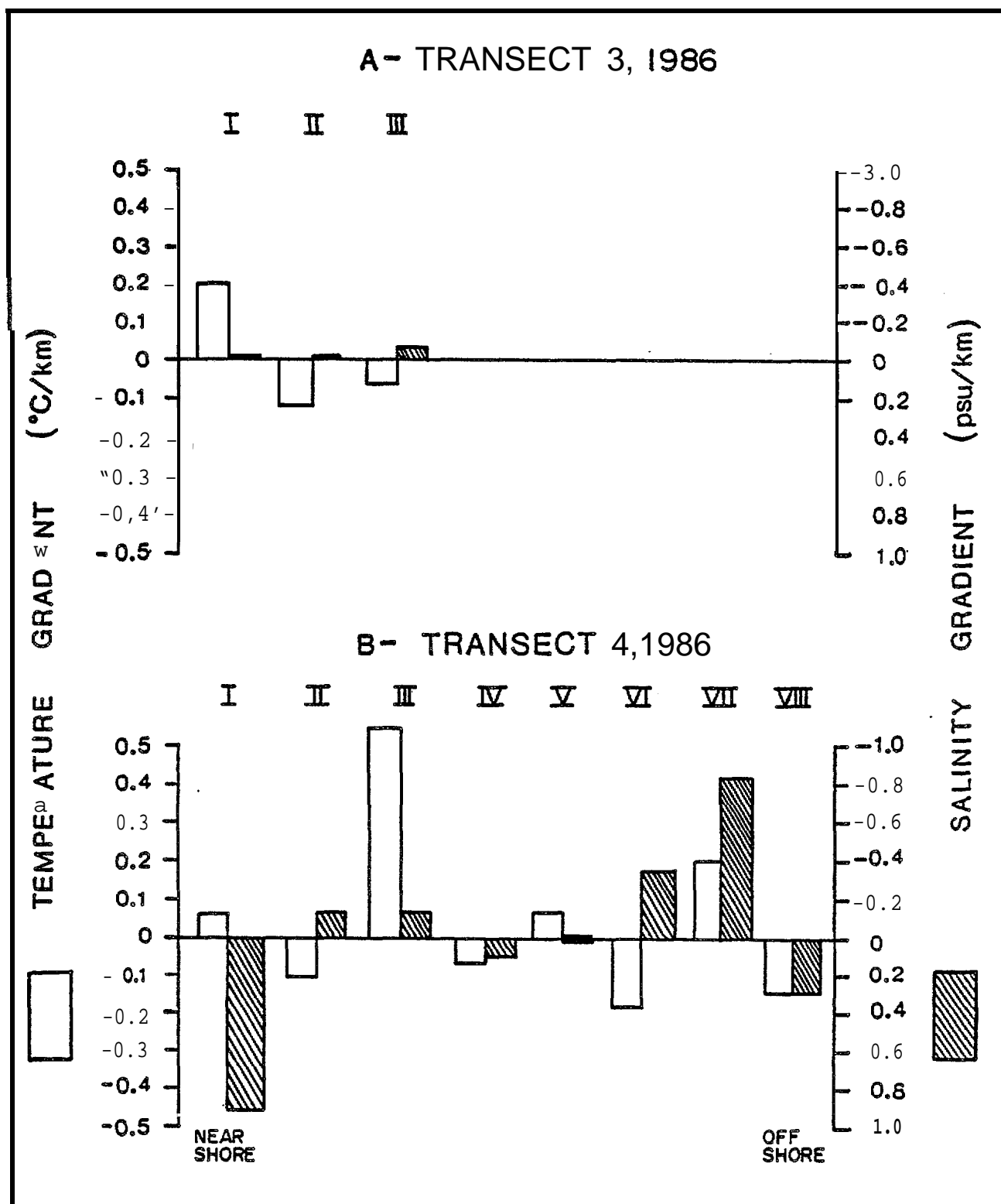




**FIGURE 66\*** Comparative magnitudes of selected horizontal gradients in temperature and salinity observed in September 1985 along (A) boat transect 1, and (B) boat transect 2.



**FIGURE 67.** Comparative magnitudes of selected horizontal gradients in temperature and salinity observed in September 1986 along (A) boat transect 1, and (B) boat transect 2.



**FIGURE 68.** Comparative magnitudes of selected horizontal gradients in temperature and salinity observed in September 1986 along (A) boat transect 3, and (B) boat transect 4.

The lack of coincidence of some temperature and salinity gradients implies that salinity gradients **will** not always be evident **from** maps of sea surface temperature derived through remote sensing. Salinity gradients are important in their own right because changes in salinity determine, for the most part, changes in water density. Also, salinity is a more conservative water property than is temperature, as salinity is modified less by vertical heat exchanges (solar insolation or turbulent heat **losses** to the atmosphere). For this reason, some significant frontal features, **including zones of convergence and possible zooplankton aggregation** could be overlooked if one considered only sea surface temperature. On the other hand, the availability of synoptic and repeated data about water temperature (and color), as derived from the remote sensing techniques, is a considerable advantage. The data from this study showed that satellite, airborne and boat-based data are complementary. No one or two of these three methods can provide all of the data needed to characterize spatial and temporal changes in water masses.

### Discussion

The distributions of physical oceanographic features over the Eastern Alaskan continental shelf and slope were examined by means of data collected from a boat in 1985-86, through remote sensing from an aircraft and satellite in 1985-86, and from a review of the literature and historical data. Sea-ice and wind patterns in 1985-86 were also summarized.

#### Water Masses

The water column of the study area **can be** categorized as zones or layers, according to the vertical distribution of density (and salinity):

- An upper layer, extending from the surface to the upper portion of the main seasonal **pycnocline**. The depth of this layer varies from 4 to 12 m over the central and outer parts of the continental shelf. In nearshore areas (within 15 km of shore) the **pycnocline** can extend to within 2 m of the surface.
- The main **pycnocline**, which extends downward from the upper layer to depths of about 15 to 30 m outside the nearshore zone. In the shallower nearshore waters, the **pycnocline** often extends to the ocean bottom, or to a thin bottom boundary **layer**. The **pycnocline** is characterized by strong vertical gradients in temperature, salinity and density.
- The lower **layer**, occupying the deepest portion of water **column** from the base of the **pycnocline** to the ocean bottom. Although density (and salinity) exhibit weak vertical gradients within this layer, temperature can vary widely.

Lower Layer.--The lower layer consists of two distinct water masses (Fig. 50-52). Arctic Surface Water (**ASW**) is most common, being present throughout the study area in 1985 and over most of the continental shelf in 1986. This water is cold ( $<-1.0^{\circ}\text{C}$ ) and saline ( $>31$  **psu**). It originates within the Arctic Ocean through large scale exchanges between the waters of the Arctic Ocean's continental shelf and the underlying Atlantic Water in the deep basins of the Arctic Ocean (Aagaard et al. 1981). In 1986, a second water mass was also

present within the lower layer. This water originated in the Bering Sea and flowed north and east along the edge of the Alaskan continental shelf (Mountain 1974). Bering Sea Water rarely reaches as far east as the Eastern Alaskan study area. The last recorded instance of an eastward intrusion was in 1951 (Fig. .39).

Bering Sea Water (BSW) is defined by temperatures  $>0.0^{\circ}\text{C}$  at salinities of 30.0 to 32.5 psu (Mountain 1974). In September 1986, BSW with these characteristics was observed at the outermost stations on transects 1, 2 and 3. The spatial extent of the BSW was clearly evident in vertical sections of temperature (Fig. 47, 48). On the westernmost transects 1 and 2, where the Bering Sea Water was most prominent, this water type was found at depths of 20 to 110 m over the outer edge of the continental shelf and inner portion of the continental slope (water depth  $>50$  m). The core of the BSW occurred at or near 30 m depth, with a maximum temperature of  $3.4\text{--}4.1^{\circ}\text{C}$ . Farther east on transect 3, the BSW was found only over the slope, at reduced temperatures of up to  $0.75^{\circ}\text{C}$ ; it extended over a considerable depth range--25 to 125 m. This water type was not observed on the easternmost transect 4, although there was evidence of slight warming at the outermost station at depths near 50 to 75 m. The western origin of the water was clearly demonstrated by the progressive reduction in the warm subsurface core from west to east (Fig. 49). It is likely that eastward advection was occurring actively during and following the September 1986 study period. Data collected in early and mid October 1986 from the USCG vessel 'Polar Star' showed that the warm-subsurface core was then present as far east as transect 4 (temperatures  $>3^{\circ}\text{C}$ ; D. Thomson, pers. comm.).

**Pycnocline Layer.**--Within the intermediate pycnocline layer, water mass types generally followed a linear gradation from the water mass properties of the upper layer to Arctic Surface Water (ASW). Where Bering Sea Water occurred, the gradation of TS properties within the pycnocline layer still exhibited the influence of ASW, with the transition to BSW being limited to depths immediately above the BSW itself.

At some locations, another water mass type also occurred within the pycnocline and the uppermost portion of the lower layer. This water type, called Cold Halocline Water (CHW), was cold like ASW but less saline (27-31 psu). It originates as a mixture of Arctic Surface Water with the cold fresh water that arises from melting of the seasonal ice over the continental shelf. Fresh water from the Mackenzie River and other local rivers may also contribute to this water type, but this could occur only after cooling of the river water to near-freezing temperatures. Mixing of the meltwater from 2 m of sea-ice with a 20 m layer of shelf water of average wintertime salinity of 32 psu (Melling and Lewis 1982) would result in a water column with 28 psu salinity at near-freezing temperature,

CHW was present in the westernmost portions of the study area over the middle and outer shelf in both 1985 and 1986. CHW was not clearly evident on transect 3 (sampled in 1986 only) or transect 4 (1985-1986). Given the melt and retreat of the seasonal ice cover throughout the study area, an interesting question concerning the distribution of CHW is why it was limited to the outer continental shelf and beyond in the western portion of the study area. The absence of CHW in the eastern or inshore portions of the study area suggests that it had been replaced in these regions by other water types

either through westward advection of water from Mackenzie Bay or by vertical mixing, likely with ASW upwelled from below.

Upper Layer.--The water masses **of** the upper **layer** were more complex due to the greater number of physical mechanisms influencing the upper layer, including surface heat exchanges, ice melt and horizontal **advection**. Water mass types observed within the upper layer included

1. **Nearshore** waters of **estuarine** or coastal influence--In both 1985 and 1986, narrow discontinuous bands of turbid water occurred in the nearshore portions of the study area. In 1985, this type of water occurred over **small** areas, seldom extending beyond 5-10 km from shore. Temperatures reached **0.5-2.0°C**. In 1986, the more intensive sampling revealed bands of turbid nearshore water extending west at least **to** 142°W. Surface temperatures and salinities showed considerable variation in the nearshore band, from <1°C to **>4°C**, and 21-26 **psu**. The lowest temperatures and salinities were associated with scattered bands of melting ice. A more consistently distinguishing feature of the nearshore band was the very thin surface layer, with the **pycnocline** extending to within a few meters of the surface. At and beneath the **pycnocline**, cold saline Arctic Water was present at significantly shallower depths (5-15 m) than in the adjoining and warmer inner shelf water slightly farther offshore. The width of the nearshore band was also highly variable, ranging from as little as 1 km to as much as 5-10 km from the coast or barrier islands. On one occasion, 10 September 1986, turbid water of coastal origin extended over **30** km offshore from Demarcation **Bay**. The distribution of turbid nearshore bands varied considerably with time. Within the official study area, they occurred most frequently off the **Kongakut River Delta (141.8°W)** and Demarcation **Bay**.
2. **Cold** inner and mid-shelf waters--Over most of the continental shelf, the upper layer was comparatively cold, saline and of low turbidity. These waters had the temperature-salinity characteristics of Arctic Surface water, as modified by solar insolation, melt of **local** sea-ice, and mixing with Mackenzie Bay water. In 1985, typical surface temperatures ranged from -1.5 to **0.5°C**, while salinities were in the 25-29 psu range. In **1986**, the cold waters over the inner and mid-shelf were confined to the west of **142°W**. Even in these areas, temperatures were warmer than in 1985, with surface **values** of -0.5 to 2.5°C. Salinity **levels** were similar to those of 1985, ranging from 25-28 psu.
3. Warm inner **and** mid-shelf waters--Much warmer surface waters were present in the eastern portion of the study area during September **1986** than were observed farther west in 1986 or throughout the inner and mid-shelf areas in 1985. Temperatures were **2.5-5.0°C**. Salinities were little changed from 1985--25 to 28 psu. The origin of the warm water in 1986 may have been related, **in** part, to the somewhat earlier clearing of sea-ice from the study area in 1986 as compared to 1985, resulting in greater solar insolation. Local estuarine sources may also have played a role in the warming of the surface waters over **the** inner shelf, as indicated by the persistent temperature maxima measured off the **Kongakut Delta** from **6-10**

September (see item (1) above). However, **the** satellite data (Fig. 33) strongly suggest that the increased temperature of the upper **layer** was **partly** of Mackenzie Bay origin. On the thermal imagery from 6-10 September 1986, a branch of the warm Mackenzie Bay water appeared to have been advected west into the inshore portions **of** the **study** area, extending west to **142°W**. The warm water appeared to originate as part of the core **of** warm, **turbid** Mackenzie Bay water present east of Herschel Island. This warm water separated from the main northwesterly oriented branch **along** the **continental** shelf edge, and extended due west within 20 km of the north shore of Herschel Island. West of Herschel Island, the warmer temperatures became less homogeneous, and **cold** large-scale eddies and meanders were interspersed through the generally warmer inshore waters.

4. Offshore Mackenzie Bay water--Along the eastern edge of the study area, the warm and turbid water from Mackenzie Bay was **most** prominent in offshore waters, extending from the outer continental **shelf** (over depths >50 m) across the continental slope to depths >2000 m. These waters occupied much of the **large** area of open **water** that extended unusually far offshore in early to mid September 1985. Satellite imagery suggested that the warm **water** was steered northwest along the steeply sloping shelf break past the protrusion of Herschel Island. Near the east side of the official study area, large-scale eddies and meanders were observed along the southern edge of the warm **core** of Mackenzie Bay **water**. These processes resulted in **advection** of Mackenzie Bay water into the continental **shelf** off northeastern Alaska.

The influence of Mackenzie Bay water decreased in the west part of the study area. In 1985, under prevailing easterly winds, the influence of Mackenzie Bay water was observed across **the full** width of the offshore portion **study area, albeit** at reduced temperatures in the western half. In 1986, the measurable influence of Mackenzie Bay **water** was limited to the eastern **half** of **the** offshore portion of **the** study area. In both years, strong northwest winds during mid-September reduced the effects of Mackenzie Bay water throughout the study area, through a combination of vertical mixing of the water column and strong wind-driven eastward **advection**.

#### Large-Scale Advection Patterns

The distribution of near-surface oceanographic features was strongly related to regional wind patterns. During most of August and the first half of **September** 1985, the prevailing winds were easterly. As a **result**, the comparatively warm, fresh and turbid water of Mackenzie Bay was **advected** westward into the offshore portion of the Eastern Alaskan Beaufort Sea. In September 1985, the offshore core of warm, turbid water was more prominent in Eastern Alaskan waters than had been observed in previous years from satellite imagery (cf. Fissel et al. 1985; also Fig. 20, 21 of this report). Heavy ice **conditions** in the easternmost part of the Canadian Beaufort Sea during the summer of 1985 may also have contributed to the unusual westward extent of warm fresh water in the offshore portion of the study area. The reduced eastward dispersal of **riverine** water in 1985 likely contributed to the strong

riverine characteristics of Mackenzie Bay waters advected into the Eastern Alaskan area by the prevailing easterly winds.

In 1986, easterly winds were less dominant than in 1985, and the westward **extent** of the warm freshwater of Mackenzie Bay water was reduced. The warm core of the water remained along the continental shelf edge east of the official study area. Offshore from the continental **shelf**, the influence of Mackenzie Bay water was limited to the easternmost portion of the study area in 1986.

Over the inner **half** of the continental shelf, particularly **in** the southeastern part **of** the study **area**, **advection** patterns and the properties of the surface water were more complex **in 1986** than 1985. Although the 1985 data were limited, the inner shelf waters were generally **cold**, clear and saline, with the exception of a narrow discontinuous nearshore band of turbid and perhaps warmer water. During **1986**, a general elevation in surface temperatures within the eastern inshore waters was accompanied **by** (1) evidence of westward **advection** of warm Mackenzie Bay water past Herschel Island into the inshore areas; (2) a large and more variable nearshore band of turbid and usually warmer water extending up to 30 km from shore, particularly off the **Kongakut** Delta and Demarcation Bay; and (3) sizable areas of much cooler surface waters in the form of eddies or meanders embedded within the warm inshore waters. Also of interest were the **large** gradients at depth within the nearshore **waters**; colder and more saline water was present **below** the nearshore band in **1986**, (**It is** not clear whether similar differences existed in 1985, given the limited sampling on the inner shelf, although the much **colder** surface temperatures of the inner shelf waters in "1985 make this seem unlikely.) **Along** with the more complex spatial distribution observed in 1986, the inshore areas were characterized by a high degree of time variability, with major changes occurring over periods as short as two **days**.

The remarkable differences in the inshore oceanographic regimes of the eastern half of **the** study area between 1985 and 1986 are difficult to explain. The variable wind **field** of 1986 may have been conducive to a greater **level** of **mesoscale** variability than were the more persistent easterly winds and large-scale advection patterns experienced in 1985. Large eddies and meanders over scales of a few tens of kilometers tend to be more prominent in the absence of strong winds.

During both **1985** and 1986, periods of strong northwest or west wind occurred in mid-September, and resulted in major changes in water masses. The wind caused eastward advection combined with strong vertical mixing of the water column. After each of these periods of west wind, the **warm** core of Mackenzie Bay water **was no** longer identifiable in the offshore portions of the eastern Alaskan **Beaufort** Sea. The Mackenzie Bay water had retreated eastward. Perhaps equally important, the warm fresh water in **the** surface layer had been mixed with the cold saline Arctic Water that had previously been underlying the surface **layer** of Mackenzie Bay water. In addition, heat from the surface layer was lost **to** the atmosphere. The northwesterly winds of mid-September 1985 **also** brought much pack ice into most parts of the study area. The westerly winds in **1986** **did** so to a much **lesser** degree.



The effects of large amounts of vertical mixing were **also** evident in boat-based data collected over **the** inner and middle continental shelf after the strong northwesterly winds in mid-September of 1985. (No similar data were available for 1986.) The surface layer became considerably cooler, more **saline** and deeper, and it became **less clearly** differentiated from the colder more **saline** water beneath. No boat-based observations of the narrow coastal band of warmer water were obtained after **the** strong northwesterly winds began. **However**, satellite imagery from 18 September 1985 (Fig. 27) showed a band of turbid water along the coast, extending 10-15 km from shore. The higher **turbidities** presumably reflected wave-induced resuspension of **bottom** sediments.

### Upwelling

**Upwelling** of nutrient-rich water from deeper to shallower depths may enhance primary production and increase the food supply for zooplankton. The boat-based oceanographic data demonstrated that coastal **upwelling**, driven by the dominant easterly winds, was present at least from 5 to 10 September in 1985. The upward tilting of temperature and salinity contours at depth indicated **that** the cold **saline** Arctic Water found at depth near the shelf edge was being transported shoreward onto the inner **shelf**, just seaward from the narrow band of warmer water found along the coast. The satellite and airborne data of 1985, **along** with nutrient data (Fig. 154), were **also** consistent with the occurrence of **upwelling** over **the** inner shelf. During and after the period of **strong northwest winds**, **upwelling** probably stopped, given **the** absence of **any known** driving mechanism.

In 1986, there was no evidence of **upwelling** in the subsurface TS data from the inner **shelf** and nearshore zones, in the remote sensing data, **or** in the nutrient measurements (Fig. 154). **The** absence of any pronounced coastal **upwelling** in 1986 was expected because easterly winds were less prevalent from **mid-August** to mid-September in 1986 than in 1985.

These 1985-86 data, **along** with pre-1985 data, show that episodes of coastal **upwelling** often occur within the study area, but may not occur in **all** years. Based on 11 temperature and salinity data sets examined in this study, spanning the years 1951-86, strong evidence of **upwelling** was evident in 4 years, including 1985, and there was evidence of a lesser or indeterminate degree of **upwelling** in four others. In three data sets (two in 1957; 1986), there was no evidence of **upwelling**.

### Frontal Features

Two **large scale** fronts (many kilometers in length) occur commonly in the study area. These are (1) **the** front along the southern edge of warm and **less saline** Mackenzie Bay water, generally near the continental shelf edge in the eastern part of the study area, and (2) the boundary between **turbid** nearshore waters and **less turbid**, and generally cooler, **inner shelf** waters. The first type of front occurs **far** offshore in the eastern part of the study area, although it can **extend** westward **well** into the study area during prolonged periods of easterly winds, as in 1985. The nearshore front appears to have a spatially intermittent character, often being limited to **or** more prominent near the mouths of lagoons or bays.

Other large-scale fronts also occur intermittently. In 1985, frontal features separated surface waters of low ( $<0.5^{\circ}\text{C}$ ), intermediate. ( $0.5$  to  $2.0^{\circ}\text{C}$ ) and warm ( $>2.0^{\circ}\text{C}$ ) temperature over the continental shelf. The locations of these fronts varied considerably over a one week period. In 1986, large-scale thermal gradients were **also** present, but they tended to have a north-south orientation, separating **cold** water in the west from warm water in the eastern half of the study **area**.

The airborne data of 1985-86 and the satellite imagery of 1980-86 suggest that meanders and eddies associated with fronts can bring warmer water onto the continental **shelf** from farther offshore, or from the east. Typical diameters of these localized features, as resolved in the satellite **imagery**, ranged from a few kilometers or less up to **10-15** km. Higher resolution sampling in the horizontal **plane**, as conducted from the aircraft and the boat, revealed large gradients over spatial scales as **small** as a few hundred meters. In 1986, prominent offshore extensions or filaments of the turbid nearshore waters also occurred, particularly off the **Kongakut** Delta and Demarcation Bay.

During and following the periods of northwest or west wind in mid-September of both 1985 and 1986, the surface gradients in temperature were much reduced, due to the eastward advection and strong vertical **mixing** associated with the intense wind events. Variation in surface water temperature was at most  $1^{\circ}\text{C}$  throughout the ice-free portion of the study area. No well-defined fronts were evident in the satellite imagery obtained after **westerly** winds.

Gradients in surface salinity did not always coincide with gradients in temperature. Thus remote sensing data from aircraft and satellites, which are based on thermal and color sensors, may not identify all important frontal features. Salinity fronts, indicative of differences in the density of surface waters, may be important in identifying possible areas of surface convergence and aggregation of **zooplankton**. It **may be** possible to infer surface salinity from water color (**Borstad unpubl.**) but the relationship between these quantities is not a simple one. Water **color** depends on the concentrations of dissolved **organics** and chlorophyll as **well** as suspended sediments. In particular, salinity vs. water **color** relationships established for offshore areas **would** not be **valid** for areas closer to the sources of sediments--river mouths and shallow areas where bottom sediments are resuspended under wave action.

#### Water Masses vs. Bowhead Whales

In September 1985 whales were rarely observed within the official study area although they were observed in some numbers just to the east **along** the Yukon coast off **Komakuk**. In early September 1986, bowhead whales made more extensive use of coastal portions of the study area as far west as  $142^{\circ}\text{W}$  (see '**Bowheads**' section, later). A major difference in water property distributions was evident between the two years in the southeastern portion of the study area. In 1986, the inner shelf waters were considerably warmer, apparently due to greater westward **advection** of Mackenzie Bay water on the shelf proper, combined with possibly enhanced solar insolation. Moreover, the turbid nearshore waters extended over a considerably larger area in 1986, with occasional instances of filaments of turbid warm water extending 10-30 km from shore. Also present in the nearshore zone during 1986 was cold saline Arctic

water. This occurred immediately beneath the thin, turbid upper **layer**. As a result, at the boundary between the nearshore and inner **shelf** waters there were strong horizontal gradients at depths of **5-15 m** (Fig. 58, 59). It seems **unlikely that** similar strong horizontal **gradients** existed in 1985. Similar **but** more intense frontal conditions occur more frequently off the Yukon coast, particularly between Shingle and King Points in Mackenzie Bay, **e.g.** in 1985 (Bradstreet and Fissel 1986; Bradstreet et al. 1987).

Thus **it** seems reasonable to hypothesize that the presence of bowhead **whales** in nearshore areas may be related--at **least** sometimes--to the occurrence of a **well** developed nearshore band of turbid water with underlying **cold**, saline Arctic water extending nearly **to** the surface, accompanied by generally warmer and less saline water farther offshore over the inner **shelf**. The resulting strong gradients, in both the horizontal and vertical, may provide an aggregation mechanism for concentrating zooplankton.

### Conclusions

1. Water masses in the study area can vary considerably from year to year, and within years. The variability results from the peripheral location of the study area relative to the sources of water masses originating in the Mackenzie Bay area and in the **Bering-Chukchi** Sea region.
2. The water column consists of three reasonably distinct zones: an **upper layer**, the **pycnocline**, and a **lower layer**.
3. In the upper layer, extending from the surface to depths of **4-12 m**, there is **little** vertical change in temperature, salinity or density. However, temperature and salinity vary considerably with location and time.
4. The main **pycnocline** extends from the bottom of the upper **layer** down to **15-32 m**. Salinity and density increase and temperature decreases with increasing depth.
5. The lower **layer**, extending from the **pycnocline** to the sea **bottom**, has comparatively weak vertical gradients in salinity and **density**, although there can be **large** temperature changes.
6. In September 1985, the **lower** layer consisted exclusively of cold, saline Arctic Surface Water (**ASW**), which originates at **depths of 0-200 m** in the Arctic Ocean proper.
7. In September 1986 but not 1985, a very prominent subsurface core of **much** warmer Bering Sea Water (**BSW**) was present over the outer continental **shelf** and continental slope. Maximum temperatures of **3-4°C** were observed. The occurrence of BSW within the study area is apparently **rare**, based on the limited previous data from this **area**.
8. Within the **pycnocline**, water mass types were either (a) a mixture of the deeper ASW with the overlying upper layer; or (b) **Cold Halocline Water (CHW)**. CHW originates as a mixture of **ASW** with the **cold**, fresh

upper layer present during seasonal ice melt. **CHW** occurred **most** frequently in the western offshore portion of the study area.

9. The influence of the massive freshwater outflow from the Mackenzie River extends into the Eastern Alaskan study area to varying degrees. Warm, fresh, turbid water of Mackenzie Bay origin was present in the upper layer over the offshore portion of the study area, from the edge of the continental shelf to **abyssal** depths.
10. The influence of Mackenzie Bay water was more prominent in early September 1985 than in September 1980-84 or 1986. The strong influence of Mackenzie Bay water in **1985** resulted from an extended period of easterly winds combined with heavy ice conditions in the easternmost part of the Canadian Beaufort Sea.
11. The characteristics of the upper layer differed **at** different distances from shore. The influence of the Mackenzie River was usually strongest far offshore, **at** and beyond the shelf break. Over the continental shelf, the surface **layer** in the nearshore zone differed from that farther offshore over the inner and middle shelf.
12. The nearshore water mass showed strong **estuarine** influence. It occurred as a thin, narrow discontinuous band of turbid water **along** the coast in both 1985 and 1986. The **areal** extent of this water type was larger in 1986 than **1985**. Beneath the thin **surface** layer, **cold** saline Arctic Water was found within 5-15 m of the surface.
13. In 1985, over most of the continental **shelf** beyond the nearshore zone, the upper layer was characterized by cold (**<1.5-2.5°C**) saline Arctic water. In 1986, this cold water in the upper layer was generally confined to areas west of **142°W** over the inner and middle shelf.
14. **In 1986**, the upper layer over the eastern portions of the inner and middle shelf was "much warmer (**2.5-5.0°C**). The additional heat content was **likely** due, in **part**, to greater **solar** insolation resulting from earlier ice clearing in August 1986 than in August 1985. Some of the heat may also have been due to advection of water from Mackenzie Bay or warm discharges from **local** estuaries.
15. The distribution of water masses and sea-ice changed markedly **in** mid-late September of both 1985 and 1986, as a result of strong northwest or west winds. Following the strong winds, water of Mackenzie Bay origin was no longer identifiable in the Eastern Alaskan Beaufort Sea. High levels of vertical mixing had resulted in cooler, more saline, and more homogeneous surface water. Northwest winds in mid-September 1985 brought much ice into the study area; west winds in 1986 had much **less** effect on ice.
16. CTD and nutrient data provided strong evidence of coastal **upwelling** in the inner **shelf** zone during the 5-10 September 1985 period, but not in the 10-19 September 1986 period. This difference was to be expected, given the more consistent easterly winds in 1985.

17. **Large scale** frontal features occur **in** most years **within** the study area. **One front** occurs along the inshore **side of the** warm, **less saline** Mackenzie Bay water near the **shelf break**. This front is strongest **in** the eastern part of the **study** area. Another front separates **turbid** nearshore waters from **cooler** and clearer **inner** shelf waters. **Other large scale** frontal features were more **ephemeral**, differing considerably between **1985** and 1986.
18. Airborne and satellite remote sensing suggested that meanders and eddies, **likely of** offshore **origin, were** present **within the cold, saline** surface waters over the inner **shelf**. **Typical diameters**, as resolved in satellite **imagery**, ranged up **to 10-15 km**.
19. Intense frontal features over spatial scales as **small** as a few hundred meters were detected by higher resolution sampling from **the** aircraft and boat,



## ZOOPLANKTON AND HYDROACOUSTICS\*

Introduction

Marine **zooplankton** is the **major** type of food utilized by **bowhead whales** that feed in the study area. Stomachs of bowheads taken during **autumn** near **Kaktovik** contain mainly **copepods** and **euphausiids**, usually with **only small** contributions of other **taxa** (Lowry and Frost 1984; Lowry et al. 1987). There have been some surveys of the species composition and numerical abundances of the **zooplankton** in the **Beaufort** Sea (e.g. Homer 1981). However, before 1985 **virtually** no data were available on the biomass of **zooplankton** within the study area or on the vertical and horizontal distribution of **zooplankton** patches. In addition, patterns of **zooplankton** distribution had not been examined in relation to physical factors (e.g. temperature and salinity) that are known to affect zooplankton in other areas. Also, few data were available on the caloric content of the **zooplankton** in or near the study area in late summer or fall. All of these data are important in evaluating the importance of the study area to bowhead whales.

The primary objectives of the two year **zooplankton** and **hydroacoustic** portions of the study were to provide data to fill these gaps by determining (1) the broad-scale horizontal and vertical distribution patterns of **zooplankton** biomass within the southern portion of the study area, (2) the **fine-scale** characteristics of **zooplankton** near concentrations of feeding whales, (3) the caloric content of the major species and groups of **zooplankton** that comprise the diets of **bowhead** whales, viz. **small and large copepods, mysids, euphausiids, etc.**, and (4) physical and chemical characteristics of the water masses (e.g. temperature, salinity and chlorophyll levels) that are believed to affect zooplankton distribution and abundance in the study area.

Both the 1985 and 1986 field seasons were planned around 25-d charters of a 13-m boat, the 'Annika Marie'. The intent during each season was to conduct a broad-scale survey of **zooplankton** in the southern part of the study area early in the field period (prior to the arrival of many whales), and then to conduct fine-scale surveys of **zooplankton** near feeding whales. If time allowed, additional broad-scale surveys were planned at the end of the field season. A combination of quantitative **hydroacoustic** surveys plus net sampling was planned during both broad- and fine-scale surveys. Net sampling would provide specific data on biomass, species composition and caloric content of the zooplankton at selected locations. The **hydroacoustic** surveys, after calibration by net sampling, would provide far more extensive data on the vertical distribution of biomass at all locations along transects.

It was expected that this approach might have to be modified in response to the vagaries of ice, weather, and **whale** distribution, and that was indeed the case. In 1985, ice, that had covered much of the study area until late August moved offshore by early September, and broad-scale surveys of **zooplankton** began on time. However, there were virtually no whales within the

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study area' in early and mid September 1985, so fine-scale work near feeding **whales** was not possible. Ice covered most of the study area after 17 September, and boat-based work within the study area was not possible after 19 September. Despite these problems, the 1985 field program provided much new information **about** the vertical and horizontal distribution of **zooplankton** within the Eastern Alaskan Beaufort Sea, the patchiness of the zooplankton, and its quantitative composition (see Griffiths et al. 1986; the 1985 results are also summarized in this report). During the 1986 **field period**, the study area was virtually ice-free. Feeding **whales** were already present by early September, so fine-scale sampling of zooplankton near concentrations of bowhead whales was conducted on 4-7 September, immediately after the arrival of the boat in the study area. Samples **were** collected at five sites with whales present or where whales had been observed within the preceding 24 h. Three sites were within the official study area, just off the **Kongakut Delta**. Two sites were slightly farther east in Canadian waters, but west of Herschel Island. The remainder of the 1986 field season (10-19 September) was devoted to broad-scale **zooplankton** sampling within the official study area.

In October of 1986, additional zooplankton sampling was conducted over the Alaskan Beaufort Sea as a whole. These samples were collected from the icebreaker 'Polar **Star**' along five transects extending perpendicular to shore from about the 50 m to the 2000 m contours. Transects were spaced between Pt. Barrow and Demarcation Bay; the easternmost two of these transects were near the eastern and western boundaries of our primary study area. The resulting data allowed us to compare the zooplankton over the continental shelf in our official study area (as sampled from the 'Annika Marie' in September of both years and the 'Polar **Star**' in October 1986) with zooplankton farther north and west (as sampled from 'Polar **Star**' alone). The 'Polar **Star**' results **also** provided information on the late season caloric content of specific **zooplankters** within the Alaskan Beaufort Sea as a whole.

The **zooplankton** data from 1985 and 1986, in conjunction with physical measurements taken in both years of the study from the boat, the aircraft, and satellite sensors (see 'Water Masses' section, earlier), were used to address one of the primary objectives of the study: to document zooplankton distribution and abundance, the physical factors affecting **zooplankton**, and the characteristics of zooplankton near concentrations of feeding whales.

#### Present State of Knowledge

##### Distribution and Species Composition

The composition of arctic **zooplankton** communities has been shown to be clearly related to physical conditions, notably temperature and **salinity** (Johnson 1956, 1958, 1963; Grainger 1965, 1975; Hopkins 1969). Based on these physical characteristics, the Arctic Ocean has been divided into three major water masses: Arctic Surface Water, Atlantic Water and Arctic Bottom Water (Grainger 1965). However, the boundaries between these water masses are somewhat arbitrary since they gradually merge into each other (Herlinveaux and de Lange Boom 1975). The cold (usually 0° to -1.9°C) Arctic Surface **Water** extends from the surface to about 150 m, and to a maximum of 250 m in the Canadian Basin. The Atlantic Layer occupies depths from 150-250 m down to 900 m; its most characteristic feature is a temperature slightly above 0°C. Arctic



**Bottom** Water occurs below 900 m and has temperatures characteristically below 0°C and a narrow range of salinities--34.90 to 34.99 psu (Grainger 1965; Herlinveaux and de Lange Boöm 1975). In addition, a fourth water mass has been identified between 50 and 100 m depth; it has been labeled as Pacific or **Bering-Chukchi Sea** Water. This water enters through the Bering Strait and is most noticeable in the **Chukchi** Sea although it does extend sporadically into the southeastern **Beaufort** Sea (Grainger 1965). A detailed description of these water masses is provided in the 'Water Masses' section, p. 23-26 and 84 ff.

Based on horizontal and vertical distribution patterns and physical measurements, Grainger (1965) describes three major groups of zooplankton in the **Beaufort** Sea and adjacent marine waters. One group is characteristic of inshore waters and the upper 100 m of offshore waters. The species that constitute this group are typically tolerant of a wide range of temperatures (-1° to about 5-10°C) and salinities (20 to 30 psu), and include the medusae Aglantha digitale and Aeginopsis laurentii, the pteropods Spiratella (= Limacina) helicina and Clione limacina, the ctenophore Beroe cucumis, and several species of copepods--Calanus hyperboreus, C. glacialis, Pseudocalanus minutus, Microcalanus pygmaeus, Metridia longa, and Oithona similis. A second group is characteristic of nearshore brackish waters along the coastlines of the **Beaufort** and **Chukchi** seas and includes the medusae Euphysa flammæa and Obelia sp., and the copepods Limnocalanus macrurus, Acartia clausi and Eurytemora herdmani. These species are typically found in waters of relatively high temperatures (1° to 12°C) and low salinities (8 to 25 psu), characteristic of nearshore brackish waters during the open water season. The third group is restricted to colder (below 1°C), more saline (>32psu), offshore deep water. Species in this group include the ostracod Conchoecia maxima and the copepods Gaidius tenuispinus, Heterorhabdus norvegicus, Scaphocalanus magnus, and Chiridius obtusifrons (Grainger 1965).

Johnson (1963) showed that there was an increase in the number of species of zooplankters to depths of 1000 to 1500 m and a decrease beyond these depths. The three most abundant species of copepods, Calanus glacialis, C. hyperboreus and Metridia longa, had wide vertical distributions (25 to 1000 m) but were most abundant in the lower part of the Arctic Surface Water and upper portion of the Atlantic Water at 50-200 m depth (Johnson 1963). Grainger (1965) recognized three groups of zooplankton in relation to vertical depth: (1) species found in high numbers in the Arctic Surface Water; (2) species associated with the Atlantic Water and the deep transitional zone of the Arctic Surface Water; and (3) species found near the surface in coastal waters. The compositions of these groups overlap with those defined above and their distributions are related to temperature and salinity (Grainger 1965).

The northeastward flow of Bering Sea Water into the **Chukchi** and **Beaufort** seas brings with it Pacific fauna from the **Bering** Sea, typified by the copepods Calanus cristatus, C. tonsus, Eucalanus bungii, and Metridia lucens (Johnson 1956, 1963). These species are termed 'expatriate' in that there is little or no local reproduction and they must be replenished from Bering Sea stocks. The nearshore distributions of these species east of Point Barrow vary from year to year; they have been reported as far east as the Alaska-Yukon border (Johnson 1956, 1963).

One factor affecting the distribution and species composition of **zooplankton** in the Beaufort Sea, particularly in nearshore waters, is the outflow of **large** rivers like the **Colville** in Alaska and the Mackenzie in Canada. It is generally believed that the outflow of this fresh water suppresses production of **stenohaline** marine species in the Beaufort Sea (Johnson 1956, 1963). However, Grainger (1975) found that the highest densities of **zooplankton** occurred in sheltered bays influenced by the Mackenzie River (e.g. Mason Bay, **Tuktoyaktuk** Harbor and Liverpool Bay). Although densities were high in these areas, species diversity was low. The **euryhaline** copepods **Limnocalanus macrurus**, **Pseudocalanus minutus**, **Acartia clausi** and **Eurytemora herdmanni** accounted for most of the organisms present.

Although **copepods** contribute more than other taxa to zooplankton densities and **biomasses** in the Beaufort Sea (over 80%; see below), other groups such as **amphipods**, mysids and euphausiids are locally abundant and constitute significant portions of bowhead diets in our study area (Lowry and Frost 1984; Lowry et al. 1987). These three groups occur all along the coast of the Beaufort Sea (Geiger et al. 1968; Grainger 1975; Homer 1978, 1979, 1981; Broad et al. 1980; Griffiths and Dillinger 1981; Griffiths and Buchanan 1982; Jewett et al. 1984). The dominant **amphipod** species vary along the coast, with **Onisimus litoralis**, **O. glacialis** and **Gammarus setosus** being the most abundant in nearshore waters (<2 m depth) and **Parathemisto libellula**, **Apherusa glacialis** and **Boekosimus affinis** being more abundant in deeper offshore waters (Broad et al. 1980; Griffiths and Dillinger 1981). **Mysis litoralis** is found in the nearshore region across the Alaskan and Canadian Beaufort Sea coasts; however, its numbers decrease with distance from shore (Homer 1978, 1979; Broad et al. 1980; Griffiths and Dillinger 1981). Three **euphausiids**--**Thysanoessa inermis**, **T. raschii** and **T. longipes**--have been reported along the continental shelf and slope of the Alaskan and Canadian Beaufort Sea (Geiger et al. 1968; Grainger 1975; Homer 1978, 1979, 1981; Broad et al. 1980).

### Density of Zooplankton

Comparisons of the standing crop of zooplankton within different regions of the Beaufort Sea and among various areas of the arctic and subarctic are confounded by several factors. These include patchiness in the abundance and distribution of zooplankton on both a large scale (1000's of meters) and small scale (10's of meters), the wide variety of net and mesh sizes used in the various studies, and the fact that most authors report their results in terms of number (density) rather than biomass.

With **these** limitations in mind, some general patterns in zooplankton density have been reported. Hopkins (1969), who sampled from ice islands T-3 and Arlis II, found the Arctic Surface Layer (depths 0-200 m) to be more 'productive' (averages of 56 indiv/m<sup>3</sup>; 0.62 mg dry wt/m<sup>3</sup>) than either the Atlantic Layer (depths 200-900 m; 13 indiv/m<sup>3</sup>; 0.14 mg dry wt/m<sup>3</sup>) or the Arctic Bottom Water (depths >900 m; 3-4 indiv/m<sup>3</sup>; 0.04 mg dry wt/m<sup>3</sup>). In all cases, **copepods** (particularly **Calanus**) contributed most to the **zooplankton** biomass; their average **contributions** in the Arctic Surface, Atlantic and Arctic Bottom layers were 83, 85 and 89%, respectively (Hopkins 1969). Similarly, in the eastern high arctic, **copepods** constituted 79% of zooplankton biomass in the upper 150 m of Lancaster Sound and 84% in the upper 150 m of NW Baffin Bay (Sekerak et al. 1976a, 1979; Buchanan and Sekerak 1982).

Other groups that occasionally contribute significantly to zooplankton biomass include hydromedusae, euphausiids, amphipods, mysids, chaetognaths, pteropods, decapods and larvaceans (Hopkins 1969; Sekerak et al. 1976a, 1979; Buchanan and Sekerak 1982; Griffiths and Buchanan 1982). Any of the above groups may be locally abundant and at times overshadow the importance of copepods. These types of local abundance have been reflected in the stomach contents of bowhead whales. The stomachs of eight bowheads taken at Kaktovik (Barter Island) in late summer contained copepods (66% of volume), euphausiids (31%), mysids (1%), and amphipods (0.5%). Three additional whales taken more recently at Kaktovik contained mainly small copepods, mysids, euphausiids and gammarid amphipods (Lowry et al. 1987). At Barrow euphausiids contributed 90% of the diet in autumn (n = 2; Lowry and Frost 1984). Copepods contributed 0-99.7% of the stomach contents of various whales.

Previous data on the abundances (no./m<sup>3</sup>) of the major zooplankton groups near Kaktovik, in the Herschel Island area, and the outer Mackenzie Delta region have been compared by Griffiths et al. (1986). Overall, the abundances are much higher than the 56 individuals/m<sup>3</sup> reported by Hopkins (1969) for the Arctic Surface Layer of the Arctic Ocean farther north. This suggests that the southern margin of the Beaufort Sea is more productive than the Arctic Ocean in general. This is to be expected since nearshore waters of the Beaufort Sea are relatively ice free during summer, and receive more nutrients from the land than does the permanently ice-covered portion of the Arctic Ocean.

Pre-1985 data suggest that zooplankton abundance in the Barter Island area (avg: 137 indiv/m<sup>3</sup>) may be lower than off the Mackenzie Delta (avg: 1176 indiv/m<sup>3</sup>) or near Herschel Island (avg: 1103 indiv/m<sup>3</sup>) (Table 5). However, the results in Table 5 are not totally comparable since the confounding factors of variable mesh size, tow type and sampling date cannot be eliminated.

In summary, based on temperature and salinity patterns, the Arctic Ocean has been divided into three main water masses: the Arctic Surface Water, the Atlantic Layer and the Arctic Bottom Water. The zooplankton has similarly been divided into three groups which tend to coincide with these water masses. Copepods (particularly the genus Calanus) contribute most of the zooplankton biomass. Zooplankton abundance generally is highest in the Arctic Surface Layer and nearshore brackish waters, and lower in the Atlantic Layer and Arctic Bottom Water.

#### Materials and Methods

Zooplankton is known to occur in patches or layers of variable size, e.g. 10's to 1000's of meters wide (Mackas et al. 1985). To determine the food available to bowhead whales, it was necessary to estimate both the spatial extent of the patches and the biomass available within and between patches. To accomplish this, we conducted co-ordinated hydroacoustic surveys along transects and net sampling at specific stations on those transects. Hydroacoustic surveys with quantitative high-frequency echosounders provided a way to determine the relative biomass at each depth along various transects, and to reveal the dimensions and locations of patches of concentrated zooplankton. Net sampling provided a way to estimate the actual biomass of

Table 5. Abundance (no. /m<sup>3</sup>) of major zooplankton groups during previous studies in the Alaskan and Canadian Beaufort Sea.

	<b>Kaktovik<sup>a</sup></b>	<b>Mackenzie Delta<sup>b</sup></b>	<b>Herschel Island<sup>c</sup></b>
Date	Sept 78	<b>Jul 73, Aug 51</b>	<b>Jul 73, Sept 74</b>
Depth Range (m)	15-25	4-27	26-90
Mesh Size (pm)	505	<b>73</b> 282	73 579
<b>Hydrozoan</b>	4.2	<b>3.5</b>	0*5
Copepods	132	<b>1149</b>	<b>1103</b>
Mysids	<b>0.5</b>	<b>7.5</b>	<b>+<sup>d</sup></b>
<b>Amphipods</b>	0.6	<b>15.8</b>	<b>+</b>
Euphausiids	<b>x<sup>e</sup></b>		
Total	137	1176	1103
Number of Samples	4	4	5

<sup>a</sup> Homer (1979), double oblique tows, September data.

<sup>b</sup> Grainger and Grohe (1975), vertical tows, July-August data. "

<sup>c</sup> **Grainger and Grohe** (1975), vertical tows, July-September data.

<sup>d</sup> + means present but **less** than 1/m<sup>3</sup>.

<sup>e</sup> x means present but less than 0.1/m<sup>3</sup>.

**zooplankton** at selected locations inside and outside patches, and to obtain data on the species composition, sizes, and caloric content of the **zooplankters**. One **goal** during each year of the study was to **develop a** regression relationship that could be used to convert relative biomass data from **hydroacoustic** surveys into absolute biomass.

Most boat-based sampling was conducted from the 'Annika Marie', on 4-18 September in 1985 and 4-19 September in 1986. Locations of sampling stations and of **hydroacoustic** transects were determined using a Magnavox 4102 satellite navigation system. In **1985**, we completed two **SSW-NNE** transects from shallow waters out to the 200 m contour (1985 Boat Transects 1 and 2), plus another transect out to the 40 m contour (1985 Boat Transect 4; Fig. 69). In 1986, we sampled four **SSW-NNE** transects from nearshore waters out to the 200 m contour (**1986** Boat Transects **T1** to T4; Fig. 69), plus ten shorter transects near concentrations of whales (1986 Boat Transects A to J; Fig. 70 and 71). An additional five on/offshore transects were sampled in October **1986** during the 'Polar Star' cruise over depths 50 m to 2000 m (Fig. 72).

#### Net Sampling of Plankton

In 1985, net sampling was conducted at 12 stations along the three **hydroacoustic** transects (see Griffiths **et al.** 1986, p. 66-71, for **sampling** details). During 1986, net sampling was conducted at a **total** of 29 **stations**,

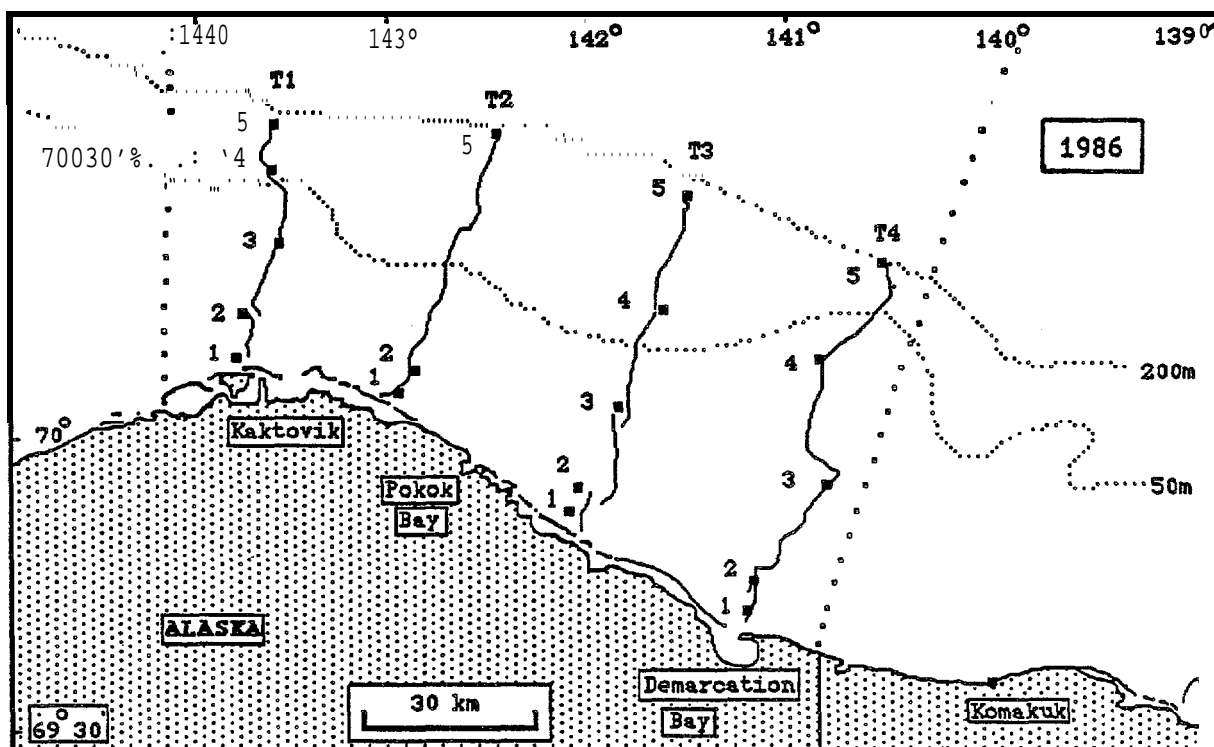
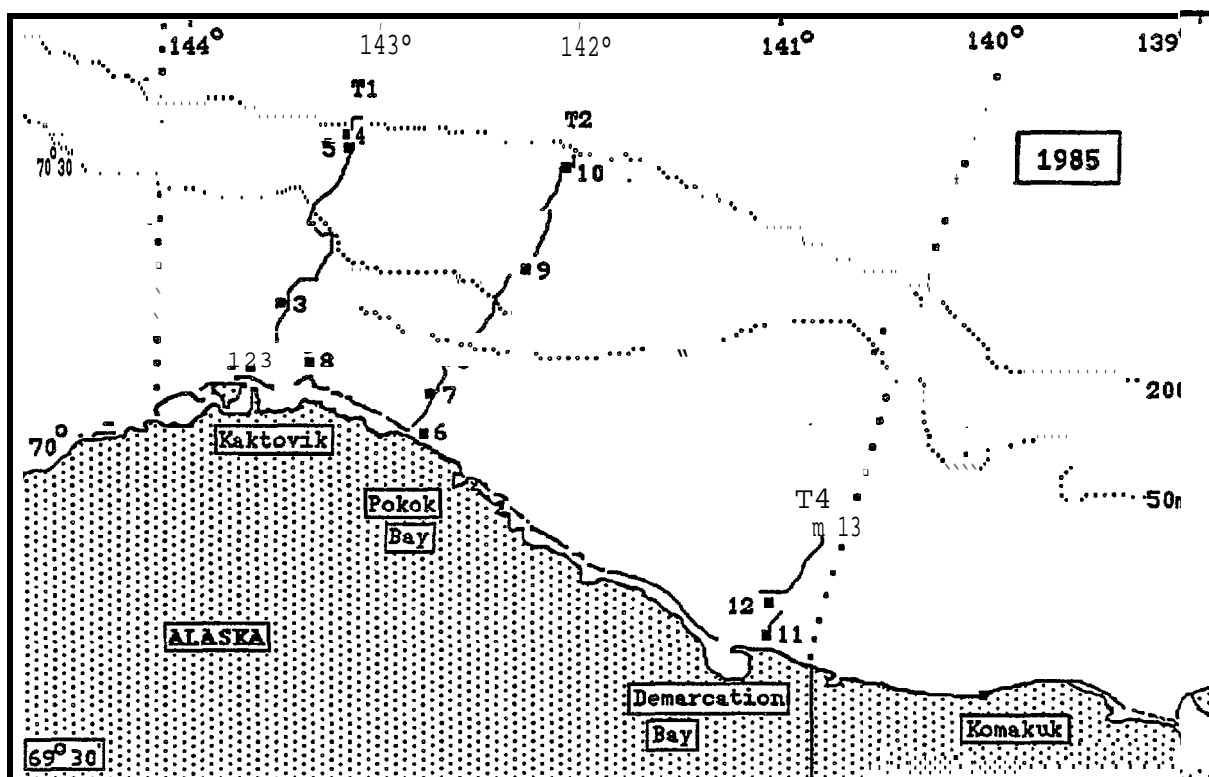


FIGURE 69. Locations of hydroacoustic transects and specific stations sampled for zooplankton and/or physical measurements in September 1985 and 1986. Depth contours are from hydrographic charts, and are approximate.

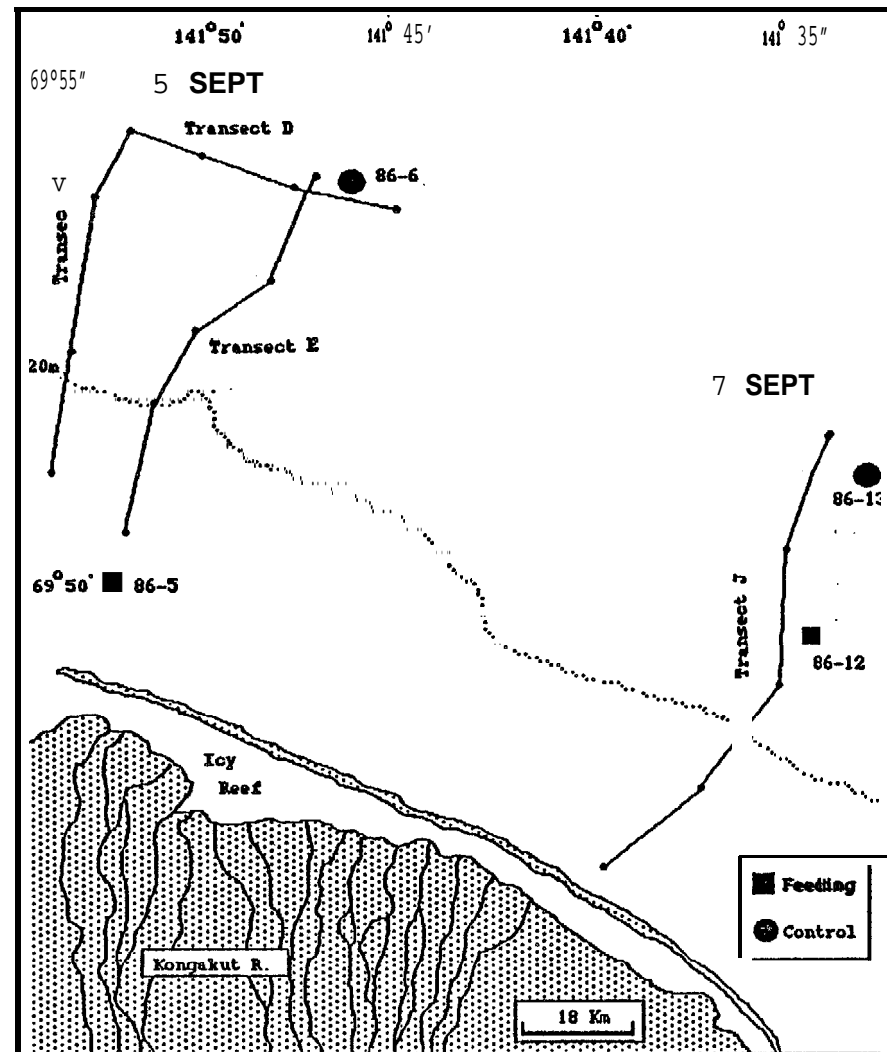
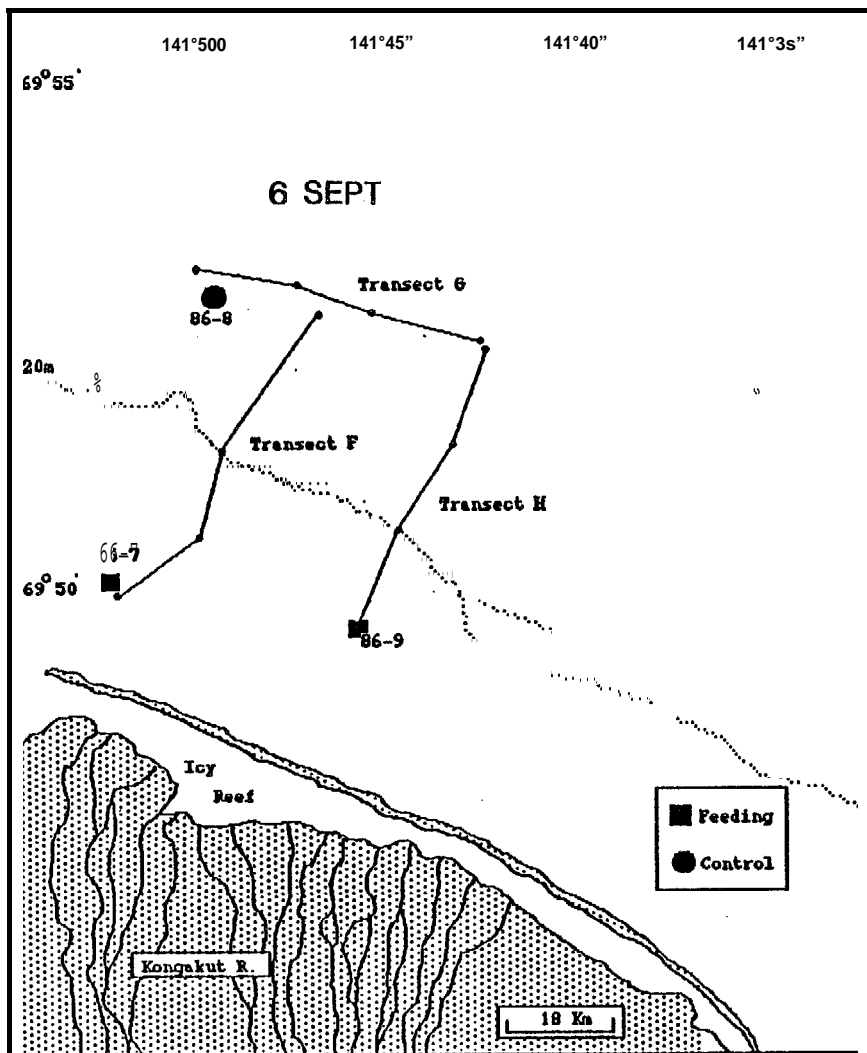


FIGURE 70.' Locations of hydroacoustic transects and specific stations sampled for zooplankton and physical measurements at and near feeding bowheads in Alaskan waters, 5-7 September 1986.

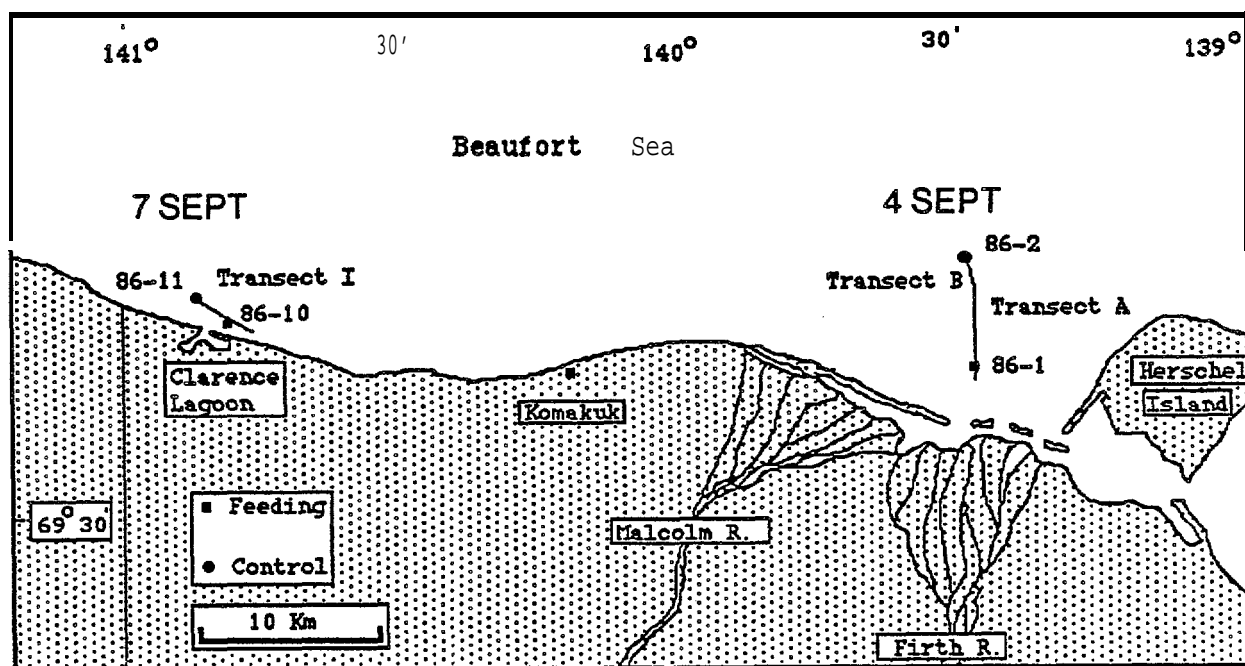


FIGURE 71. Locations of hydroacoustic transects and specific stations sampled for zooplankton and physical measurements near feeding bowheads in Canadian waters, 4 and 7 September 1986.

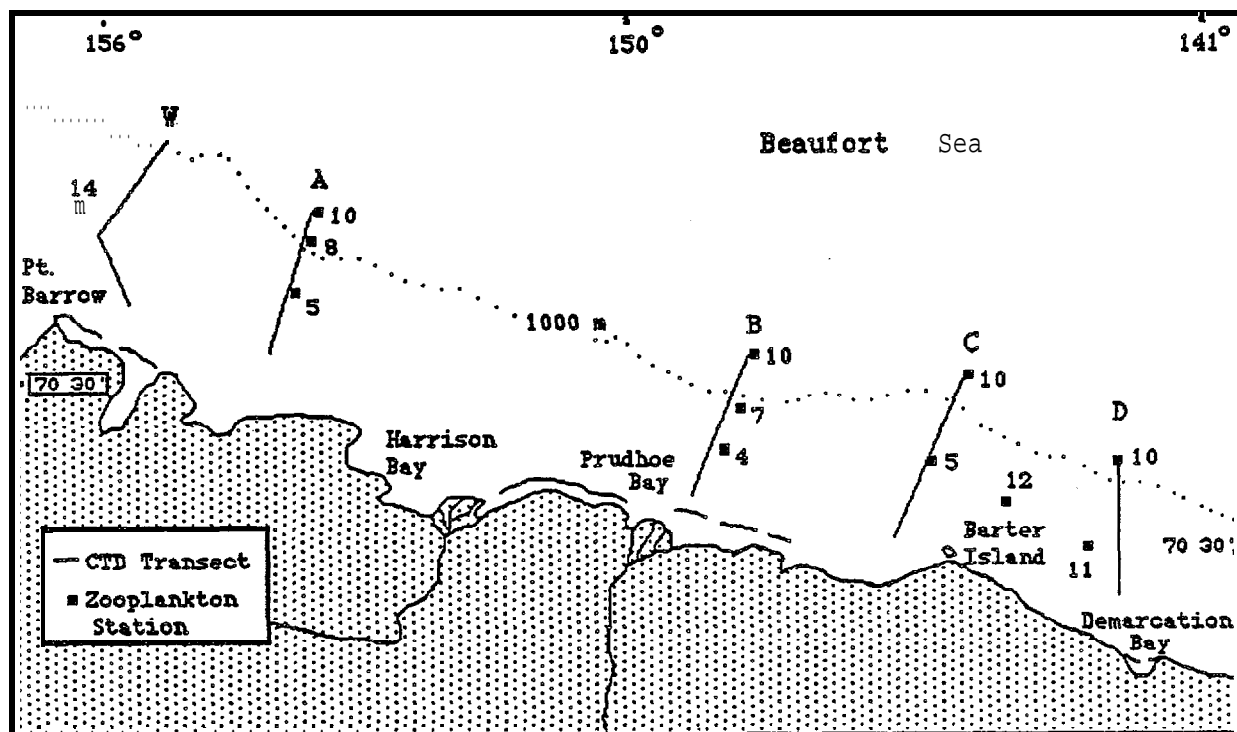


FIGURE 72. Locations of CTD transects and specific stations sampled for zooplankton during the 'Polar Star' cruise across the Alaskan Beaufort Sea, October 1986.

18 **along** the four broad-scale transects (Transects T1 to T4) and 11 **along** the ten **shorter** transects near concentrations of whales (Transects A to J; **Table 6**). In October 1986, 12 stations were sampled along the five transects between Pt. Barrow and Demarcation Bay (**Table 7**).

The stomachs of bowhead whales taken in our study area contained mainly large (>2 mm length) marine **zooplankton** like the herbivorous **copepod** *Calanus hyperboreus* and the euphausiids *Thysanoessa* spp. (Lowry and Frost 1984). These large organisms were selected as the focal points of the present study. To facilitate their capture, we used only large mesh nets (0.5 mm) during both years of the study. These nets capture **zooplankton** as small as 1.0 mm long; such small **zooplankters** were found to be important in parts of our study area.

Oblique Bongo Tows.--In both 1985 and 1986, oblique tows were performed using a bongo frame fitted with two 0.61 m diameter plankton nets (mesh size 0.5 'm) and a **flowmeter** (General **Oceanics** Inc., model 2030). In samples collected from the 'Annika Marie', the nets were towed at approximately 1 m/s and sampled the water column during both descent and ascent. In shallow waters (<40 m), this descent-ascent cycle was repeated from three to ten times, depending on depth, in order to obtain a tow of sufficient duration to compare with tows in deeper waters. In 1985, one oblique tow was performed at each of the 12 stations where ice conditions permitted. The maximum target depth **at** each 1985 station was determined from the hydroacoustic system to ensure that all zooplankton concentrations were included. In September 1986, one oblique **zooplankton sample** was **taken to** a maximum depth of 50 m at each of the 29 stations. At stations where the **hydroacoustic** system detected zooplankton concentrations below 50 m depth, an additional oblique tow was taken **to** include these concentrations. This situation occurred only once, at Station T2-5 **on** Transect 2. During the 'Polar Star' cruise, the nets were **towed** at approximately 1 m/s and the descent-ascent **cycle** was done only once. In all of the above cases, actual maximum depth of oblique tows was computed from wire angle and the amount of wire out. Depth of tow and "water. depth at each 1986 station are shown **in** Tables 6 and 7 (see **Griffiths** et al. 1986, p. 68-70, for corresponding details on 1985 samples).

Horizontal Bongo Tows.--In both years, sampling depths were selected based on results from the **hydroacoustic** system. Horizontal tows were taken within and outside zooplankton layers at **all** stations where this was feasible. In addition, surface tows were taken in **1986 but** not in 1985. All 1985 horizontal tows were collected using the standard bongo assembly and **flowmeter** described above. An upward-looking depth sounder transducer (Apelco Ranger model 1650) was attached to the bongo frame to **control sampling** depth in **real** time. A total of 28 horizontal tows were taken in 1985. For details of the **1985** sampling, see Griffiths et al. (1986, p. 71).

In September 1986, the net assembly described above, but without the upward looking echosounder, was used to collect one surface (depth 1.0 m) sample from each of the 29 stations (**Table 7**). The samples were taken by towing the nets just below the surface at approximately 1 m/s for five minutes before retrieval. It was not possible to keep the nets out of the influence of the prop-wash during the surface tows.



Table 6. Summary of samples collected in the Eastern Alaskan Beaufort Sea, 4-19 September 1986. CTD = conductivity/temperature profile, SD = secchi disc, SB = surface bongo tow, OB = oblique bongo tow, HB = horizontal bongo tow, WS = water sample, ADT = Alaska daylight time. Level of analysis for zooplankton identification, 1 = 'to major groups', 2 = 'to species'. See Griffiths et al. (1986, p. 68-70) for corresponding 1985 data.

Station	Sample		Water Depth (m)	Date (Day/Mo/Yr)	Time (ADT)	Location	Level of Analysis
	Type	Depth (m)					
Station 86-1	cm	15.0	17	04/09/86	0920	69°35.7'N 139°31.6'W	
	SD	3.3			0920	69°35.7'N 139°31.6'W	
	SB	0.0			1013	69°35.7'N 139°31.6'W	2
	OB	16.0			1040	69°35.8'N 139°28.9'W	2
	HB	13.0			1101	69°35.6'N 139°29.4'W	1
	HB	8.0			1120	69°35.8'N 139°29.7'W	1
	HB	4.0			1140	69°35.7'N 139°29.6'W	1
Station 86-2	cm	22.0	25	04/09/86	1400	69°40.3'N 139°28.4'W	
	SD	6.7			1400	69°40.3'N 139°28.4'W	
	SB	0.0			1416	69°40.4'N 139°28.7'W	2
	OB	20.0			1434	69°40.5'N 139°28.1'W	2
	HB	22.0			1445	69°40.4'N 139°28.3'W	1
	HB	10.0			1505	69°40.5'N 139°28.0'W	1
Station 86-3	CTD	10.0	12	05/09/86	0740	69°41.8'N 141°13.4'W	
	SD	1.8			0740	69°41.8'N 141°13.4'W	
	SB	0.0			0753	69°41.8'N 141°13.4'W	2
	OB	10.0			0826	69°42.6'N 141°11.0'W	2
	HB	9.0			0843	69°42.1'N 141°13.3'W	1
	HB	5.0			0948	69°42.3'N 141°13.8'W	1
Station 86-4	CTD	23.0	25	05/09/86	1055	69°45.0'N 141°10.3'W	
	SD	13.1			1055	69°45.0'N 141°10.3'W	
	SE	0.0			1117	69°45.1'N 141°10.6'W	2
	OB	23.0			1130	69°45.0'N 141°10.1'W	2
	HB	16.0			1207	69°45.1'N 141°10.3'W	1
	HB	8.0			1227	69°45.5'N 141°12.1'W	1
Station 86-5	CTD	13.0	14	05/09/86	1500	69°50.1'N 141°51.9'W	
	SD	6.1			1500	69°50.1'N 141°51.9'W	
	SB	0.0			1514	69°50.1'N 141°52.0'W	2
	OB	12.0			1525	69°50.9'N 141°53.8'W	2
	HB	10.0			1543	69°50.8'N 141°53.9'W	1
	HB	6.0			1603	69°50.9'N 141°54.0'W	1
Station 86-6	cm	25.0	27	05/09/86	1816	69°53.8'N 141°45.6'W	
	SD	17.7			1816	69°53.8'N 141°45.6'W	
	SB	0.0			1836	69°53.9'N 141°46.3'W	2
	OB	22.0			1846	69°54.0'N 141°46.5'W	2
	HB	21.0			1900	69°54.2'N 141°47.7'W	1
	HB	8.0			1918	69°54.2'N 141°48.1'W	1

Continued...

Table 6. Continued.

station	Sample		Water Depth (m)	Date (Day/Mo/Yr)	Time (ADT)	Location	Level of Analysis
	Type	Depth (m)					
station 86-7	cm	9.5	11	06/09/86	1103	69°48.9'N 141°47.8'W	
	SD	3.3			1103	69°48.9'N 141°47.8'W	
	SB	0*0			1117	69°49.4'N 141°51.9'W	2
	OB	8.0			1127	69°49.6'N 141°52.3'W	2
	HB	7.0			1147	69°49.7'N 141°51.4'W	1
	HB	8.0			1201	69°49.9'N 141°51.5'W	1
	HB	3.0			1215	69°49.8'N 141°53.3'W	1
Station 86-8	CTD	20.0	23	06/09/86	1328	69°52.6'N 141°48.3'W	
	SD	11.6			1328	69°52.6'N 141°48.3'W	
	SB	0.0			1348	69°52.9'N 141°49.6'W	2
	OB	18.0			1420	69°53.0'N 141°51.6'W	2
	HB	16.5			1430	69°52.9'N 141°50.3'W	1
	HB	7.0			1451	69°52.9'N 141°50.6'W	1
Station 86-9	cm	5.0	7	06/09/86	1704	69°48.6'N 141°46.8'W	
	SD	2.1			1704	69°48.6'N 141°46.8'W	
	SB	0.0			1717	69°48.7'N 141°47.1'W	2
	OB	5.0			1727	69°48.6'N 141°48.8'W	2
	HB	5.0			1752	69°48.3'N 141°47.4'W	1
Station 86-10	CTD	9.0	12	07 /09/86	0910	69°38.1'N 140°49.4'W	
	SD	0.6			0910	69°38.1'N 140°49.4'W	
	SB	0.0			0923	69°38.2'N 140°48.9'W	2
	OB	9.0			0931	69°38.1'N 140°48.5'W	2
	HB	7.0			0945	69°38.2'N 140°48.8'W	1
	HB	11.0			0957	69°38.1'N 140°48.7'W	1
	HB	8.0			1053	69°38.1'N 140°47.0'W	1
Station 86-11	cm	11.0	15	07/09/86	1147	69°38.7'N 140°52.4'W	
	SD	3.4			1147	69°38.7'N 140°52.4'W	
	SB	0.0			1157	69°38.8'N 140°52.7'W	2
	OB	12.0			1207	69°38.7'N 140°53.1'W	2
	HB	12.0			1218	69°38.7'N 140°53.0'W	1
	HB	6.0			1231	69°38.7'N 140°53.2'W	1
Station 86-12	CTD	18.0	22	07/09/86	1451	69°49.2'N 141°35.3'W	
	SD	3.7			1451	69°49.2'N 141°35.3'W	
	SB	0.0			1459	69°49.4'N 141°35.6'W	2
	OB	18.0			1508	69°50.0'N 141°35.5'W	2
	HB	13.0			1521	69°49.5'N 141°35.2'W	1
	HB	6.0			1536	69°49.7'N 141°37.2'W	1
	HB	15.0			1550	69°49.4'N 141°36.9'W	1

Continued. . .

Table 6. Continued.

station	Sample		Water Depth (m)	Date (Day/Mo/Yr)	Time (m)	location	Level of Analysis
	Type	Depth (m)					
Station 86-13	CTD	24.0	25	07/09/86	1625	69°51.1'N 141°33.8'W	2
	SD	12.2			1625	69°51.1'N 141°33.8'W	
	SB	0.0			1630	69°51.1'N 141°33.8'W	
	OB	21.0			1640	69°51.1'N 141°33.4'W	
	HB	17.0			1701	69°51.0'N 141°33.6'W	
	HB	8.0			1714	69°51.5'N 141°34.0'W	
<u>Transect 4</u>							
Station T4-1	cm	11.0	12	09/09/86	1430	69°42.3'N 141°17.2'W	1
	SD	4.3			1430	69°42.3'N 141°17.2'W	
	SB	0.0			1458	69°42.2'N 141°17.2'W	
	OB	10.0			1528	69°41.7'N 141°16.9'W	
	HB	4.0			1553	69°41.6'N 141°17.6'W	
	HB	8.0			1610	69°41.5'N 141°18.1'W	
	HB	10.0			1624	69°41.5'N 141°17.8'W	
Station T4-2	CTD	19.0	21	10/09/86	0800	69°44.5'N 141°11.9'W	1
	SD	8.2			0800	69°44.5'N 141°11.9'W	
	SB	0.0			0832	69°44.5'N 141°11.9'W	
	OB	18.0			0842	69°44.6'N 141°12.3'W	
	HB	19.0			0906	69°44.9'N 141°12.8'W	
	HB	10.0			0927	69°45.4'N 141°13.9'W	
Station T4-3	cm	42.0	43	10/09/86	1151	69°55.0'N 140°55.8'W	1
	SD	18.0			1151	69°55.0'N 140°55.8'W	
	SB	0.0			1203	69°55.0'N 140°55.7'W	
	OB	40.0			1215	69°55.0'N 140°55.4'W	
	HB	13.7			1229	69°55.1'N 140°55.5'W	
	HB	36.0			1254	69°54.3'N 140°55.1'W	
	HB	7.3			1314	69°54.2'N 140°55.1'W	
Station T4-4	CTD	53.0	53	10/09/86	1604	70°07.1'N 140°52.6'W	1
	SD	18.0			1604	70°07.1'N 140°52.6'W	
	SB	0.0			1617	70°07.1'N 140°52.6'W	
	OB	50.0			1627	70°07.1'N 140°52.2'W	
	HB	33.5			1641	70°07.2'N 140°52.8'W	
	HB	11.6			1705	70°07.6'N 140°53.1'W	
Station T4-5	cm	152.0	180	11/09/86	1245	70°17.8'N 140°34.2'W	1
	SD	19.8			1245	70°17.8'N 140°34.2'W	
	SB	0.0			1304	70°18.0'N 140°34.7'W	
	OB	50.0			1315	70°18.2'N 140°35.0'W	
	HB	52.0			1339	70°18.4'N 140°35.4'W	
	HB	30.0			1350	70°18.6'N 140°35.7'W	

Continued..

Table 6. Continued.

station	Sample		Water Depth (m)	Date (Day/Mo/Yr)	Time (ADT)	Location	Level of Analysis
	Type	Depth (m)					
<u>Transect 3</u>							
Station T3-1	CID	10.0	13	12/09/86	0835	69°52.2'N 142°05.0'W	
	SD	3.4			0835	69°52.2'N 142°05.0'W	
	SB	0.0			0850	69°52.1'N 142°05.0'W	1
	OB	9.0			0901	69°51.3'N 142°01.9'W	2
	HB	10.0			0916	69°51.2'N 142°01.4'W	1
	HB	5.5			0930	69°51.4'N 141°59.3'W	1
	WS	10.0			0835	69°52.2'N 142°05.0'W	
station T3-2	cm	20.0	21	12/09/86	1030	69°53.9'N 141°58.0'W	
	so	8.8			1030	69°53.9'N 141°58.0'W	
	SB	0.0			1124	69°53.8'N 141°56.9'W	1
	OB	18.0			1135	69°53.8'N 141°56.7'W	2
	HB	18.0			1148	69°54.0'N 141°55.9'W	1
	HB	10.0			1209	69°53.8'N 141°54.6'W	1
	WS	20.0			1030	69°53.9'N 141°58.0'W	
Station T3-3	CID	38.0	41	13/09/86	1000	70°03.1'N 141°49.9'W	
	SD	10.7			1000	70°03.1'N 141°49.9'W	
	SB	0.0			1021	70°03.0'N 141°49.5'W	1
	OB	35.0			1031	70°01.7'N 141°49.0'W	2
	HB	26.0			1110	70°01.7'S 141°49.7'W	1
	HB	17.0			1131	70°01.7'N 141°49.7'W	1
	WS	35.0			1000	70°03.1'N 141°49.9'W	
Station T3-4	CID	50.0	53	13/09/86	1400	70°12.9'N 141°41.8'W	
	so	16.5			1400	70°12.9'N 141°41.8'W	
	SB	0.0			1444	70°12.8'N 141°41.8'W	1
	OB	50.0			1454	70°12.8'N 141°41.7'W	2
	HB	26.0			1512	70°12.1'N 141°41.8'W	1
	HB	17.0			1530	70°12.1'N 141°41.8'W	1
	WS	50.0			1400	70°12.9'N 141°41.8'W	
station T3-5	cm	130.0	205	14/09/86	1234	70°24.3'N 141°31.9'W	
	so	18.3			1234	70°24.3'N 141°31.9'W	
	SB	0.0			1325	70°24.0'N 141°31.8'W	1
	OB	50.0			1335	70°24.0'N 141°31.9'W	2
	HB	28.0			1420	70°23.6'N 141°31.0'W	1
	HB	30.0			1438	70°23.7'N 141°30.6'W	1
	WS	200.0			1234	70°23.8'N 141°31.2'W	

Continued. . .

Table 6. Continued.

station	Sample		Water Depth (m)	Date (Day/Mo/Yr)	Time (ADT)	Location	Level of Analysis
	Type	Depth (m)					
<u>Transect 1</u>							
Station T1-1	CID	8.0	10	16/09/84	0810	70°09.2'N 143 °40.8'W	
	SD	5.2			0810	70009.2'S 143°40.8 'W	
	SB	0.0			0828	70°09.1'N 143°40.6'W	1
	OB	9.0			0840	70°09.1'N 143°40.3 'W	2
	HB	10.0			0856	70°09.2'N 143°40.5'W	1
	HB	5.0			0919	70°09.2' 8 143°37.8'W	1
Station T1-2	cm	30.0	34	16/09/86	1030	70°13.6'N 143°38.2'W	
	SD	5.2			1030	70°13.6'N 143°38.2'W	
	SB	0.0			1052	70°13.7'N 143°38.3'W	1
	OB	30.0			1103	70°13.8'N 143°38.3'W	2
	HB	10.0			1117	70°13.8'N 143°38.6'W	1
	HB	21.0			1143	70° 13.8'N 143°38.0'W	1
	HB	5.0			1200	70°14.0'N 143°37.4'W	1
Station T1-3	CID	26.0	47	16/09/86	1345	70°21.3'N 143°31.5'W	
	SD	10.7			1345	70°21.3'N 143°31.5'W	
	SB	0.0			1401	70°21.3'N 143°31.1'W	1
	OB	40.0			1416	70°21.3'N 143°30.2'W	2
	HB	29.0			1424	70°21.4'N 143°27.5'W	1
	HB	11.0			1445	70°21.4'N 143°27. 1'W	1
Station T1-4	CID	52.0	54	17/09/86	1100	70°28.7'N 143°34.7'W	
	SD	18.0			1100	70°28.7'N 143°34.7'W	
	SB	0.0			1128	70°28.6'N 143°34. 1'W	1
	OB	50.0			1137	70°28.8'N 143°33.7'W	2
	HB	33.5			1153	70°28.7'N 143°33.6'W	1
	HB	19.0			1220	70°28.7'N 143°33.2'W	1
	HB	12.5			1237	70°28.3'N 143°32.8'W	1
Station T1-5	cm	100.0	118	17/09/86	1410	70°33.2'N 143°34.2'W	
	SD	19.8			1410	70°33.2'N 143°34.2'W	
	SB	0.0			1425	70°33.1'N 143 °33.8'W	1
	OB	50.0			1433	70°33.1'N 143°33.2'W	2
	HB	15.2			1449	70°33.1'N 143°33.4'W	1
	HB	47.2			1505	70°33.9'N 143034.2 'W	1

Continued...

Table 6. Concluded.

Station	Sample		Water Depth (m)	Date (Day/Mo/Yr)	Time (m)	Location	Level Of Analysis
	Type	Depth (m)					
<u><b>Transect 2</b></u>							
<b>Station T2-1</b>	<b>CTD</b>	<b>10.0</b>	10	18/09/86	0855	70°04.5 'N 142°53.3'W	
	SD	7.9			0855	70°04.5'N 142°53.3'W	
	SE	0.0			0956	70°04.6'N 142°53.4'W	1
	<b>OB</b>	8.0			1009	70°04.8'N 142°53.6'W	2
	<b>HB</b>	8.5			1023	70°04.7'N 142°53.6 'W	1
	<b>HB</b>	5.0			1036	70°04.6'N 142°54.3'W	1
Station T2-2	<b>CTD</b>	23.0	26	18/09/86	1145	70°07.9'N 142°48.7'W	
	SD	7.9			1145	70°07.9'N 142°48. 7 'W	
	<b>SB</b>	0.0			1207	70°08.1'N 142°49. 1'W	1
	<b>OB</b>	22.0			1216	70°08.2'N 142°49.4'W	2
	<b>HB</b>	15.2			1231	70°08.3'N 142°50.0'W	1
	<b>HB</b>	6.0			1246	70°08.2'N 142°49.8'W	1
<b>Station T2-5</b>	<b>CTD</b>	<b>123.0</b>	150	19/09/86	<b>1245</b>	70°31.6'N 142°27.3 'W	
	SD	<b>21.0</b>			1245	70°31.6'N 142°27.3 'W	
	<b>SB</b>	0.0			1309	70°31.6'N 142°27.3'W	1
	<b>OB</b>	50.0			1319	70°31.7'N 142°27.1'W	2
	<b>OB</b>	<b>100.0</b>			1330	70°31.6'N 142°26.7'W	1
	<b>HB</b>	50.3			<b>1346</b>	70°31.5'N 142°27.8'W	1
	<b>HB</b>	<b>10.1</b>			1402	70°31.4'N 142°28.2'W	1

**Table 7. Summary of samples collected in the Alaskan Beaufort Sea during the cruise of the 'Polar Star', 4-17 October 1986. OB = oblique bongo tow, VT = vertical net tow, HB = horizontal bongo tow. Level of analysis for zooplankton identification, 1 = 'to major groups'; 2 = 'to Species'.**

Station	Sample		Water Depth (m)	Date (Day/Mo/Yr)	Time (ADT)	Location	Level of Analysis
	Type	Depth (m)					
<u>Transect W</u>							
Station 14	OB	50	62	04/10/86	1215	71 °49.1'N 156°30.0'W	1
	OB	50			1252		
	HB	5			0207		
	HB	10			0230		
	HB	30			0308		
<u>Transect A</u>							
Station 10	OB	50	1434	05/10/86	2125	71 °57.2'N 152°39.0'W	
	HB	110			2144		
	HB	18			2212		
	HB	20			2230		
	HB	30			2244		
	HB	50			2308		
	HB	1			2328		
Station 8	OB	50	278	06/10/86	2026	71°44.6'N 152°57.1'W	1
	OB	50			2046		1
	HB	10			2058		
	HB	25			2117		
	HB	60			2143		
	HB	1			2201		
Station 5	HB	1	64	07/10/86	0029	71°30.0'N 153°10.4'W	1
	VT	50			0100		
	VT	50			0110		
<u>Transect B</u>							
Station 10	VT	50	2070	09/10/86	0330	71°08.5'N 146°48.5'W	1
	VT	50			0340		1
	VT	50			0355		
	VT	100-200			0425		
	VT	100			0440		
Station 7	HB	1	267	09/10/86	2100	70°56.1'N 146°46.9'W	1
	OB	50			2110		
	HB	50			2130		
	HB	5			2150		
	HB	20			2225		

Continued...

Table 7. Concluded.

station	Sample		Water Depth (m)	Date (Day/Mo/Yr)	Tires (m)	Location	Level of Analysis
	Type	Depth (m)					
<u>IranSect B</u>							
Station 4	OB	30	41	10/10/86	0220	70°39.3'N 147°14.7'W	1
	H8	20			0215		
	HB	10			0235		
<u>Transect C</u>							
Station 5	VT	50	55	15/10/86	1630	70°33.2'N 144°01.5'W	2
	VT	50					1
	VT	50					1
Station 10	VT	50	1635	11/10/86	1800	71°01.2'N 143°32.9'W	2
	VT	50			1810		1
	VT	50			1830		1
	VT	100			1850		
<u>Transect D</u>							
Station 10	VT	50	1781	13/10/86	1900	70°43.1'N 140°57.1'W	2
	VT	50			1915		2
	VT	100			1930		
	VT	100			1945		
	VT	50			2000		2
Station 11	VT	50	55	14/10/86	2000	70°18.7'N 141°32.7'W	1
	VT	50			2015		1
	VT	50			2025		
Station 12	VT	50	55	15/10/86		70°26.7'N 142°51.1'W	2
	VT	50					1
	VT	50					1
<u>Transect E</u>							
Station 7	VT	50	1821	17/10/86	2245	71°25.3'N 149°54.3'W	
	VT	50			2250		
	VT	50			2300		
	VT	100			2305		



In September 1986, all horizontal tows at depth were taken using a Tareq opening and closing bongo assembly fitted with two 0-.61 m diameter nets (mesh size 0.5 mm), a flowmeter, and the upward looking Apelco echosounder. Tows were taken by attaching the bongo frame, in the closed position, to a double trip mechanism (General Oceanics model M 1000-DT) and then lowering the assembly to the desired depth. The nets were opened by sending the first messenger, and then towed at about 1 m/s for 5 min; the nets were closed by tripping with a second messenger, and the assembly was then retrieved. The depth of the nets was monitored and controlled throughout the tow by using the output of the attached echosounder. A total of 69 horizontal tows at depth were taken in September 1986 (Table 6).

Stations 86-1 through 86-13 were sampled before the upward looking echosounder could be attached to the opening and closing bongo frame. Tow depths at these stations, all of which were in water <27 m deep, were computed from wire angle and amount of wire out. For a comparison of depths derived from the echosounder vs. those computed from wire angle and wire out, see 'Results', p. 164-165.

In October 1986, horizontal tows were conducted during the 'Polar Star' cruise using the regular bongo assembly equipped with a flow meter (Table 7). Nets were lowered to the desired depth and towed for 10 minutes at approximately 1 m/s before retrieval, comparable to our 1985 procedure. Sample depths were determined from wire angle and amount of wire out.

Vertical Net Tows.--During the 'Polar Star' cruise in October 1986, ice conditions often precluded horizontal or oblique tows. In these cases, vertical net tows were used to sample zooplankton (Table 7). A 0.60 m diameter plankton net, equipped with a flow meter and a large mesh net (0.5 mm), was towed through the water column at 1 m/s. Generally, the top 50 m of the water column was sampled; however, in some cases specific depth ranges were sampled by activating a closing device during the tow (Table 7).

Tucker Trawl Tows.--To determine whether large zooplankters (e.g. euphausiids, hyperiid amphipods) were sampled adequately during horizontal bongo tows, eight samples were collected using a modified Tucker Trawl. Matched samples were taken with the standard bongo assembly at the same eight location-depth combinations. The Tucker Trawl consisted of a stainless steel frame (2.0 x 2.0 m) supporting a 6.0 m tapering knotless nylon net (stretched mesh 6.4 mm) dyed black to reduce the amount of reflected light. The use of this large mesh, coupled with the length of the net, was expected to greatly reduce the pressure wave that might otherwise precede the net. In addition, the trawl was towed by a yoke attached to the top of the frame. The vertical orientation of the net was maintained by suspending a weight from the bottom of the frame. In this way the net could be towed without a bridle, further reducing any pressure wave that might cause larger zooplankters to take avoidance reactions. The trawl was equipped with a flow meter (General Oceanics model 2030) and was towed horizontally at approximately 1 m/s for 5 min at the depth where large organisms appeared to be concentrated according to the hydroacoustic echograms. The Tucker Trawl, like the 1985 bongo nets, sampled during descent and ascent as well as during the horizontal tow.

On the 'Annika Marie' (Sept 1985-86) and the 'Polar Star' (Oct 1986), plankton samples from one side of each bongo tow and from the vertical and Tucker tows were preserved in 10% formalin.

Calorimetry and Isotope Sampling.--In both years of the study, samples from the other side of each bongo tow were used to determine the caloric content of the major groups of zooplankters (e.g. hyperiid amphipods, euphausiids, large and small copepods, etc.) and to determine their carbon isotope composition. These samples, along with samples from selected vertical tows from 'Polar Star', were placed in whirlpacs (plastic bags) and frozen. Methods for the caloric analyses are given later (p. 162). The rationale, methods and results for the isotope analyses are given in a later section (p. 369 ff).

#### Hydroacoustic Sampling of Plankton

Hydroacoustic data were collected from the 'Annika Marie' (1) during nearly all zooplankton tows in 1985 and 1986, and (2) as the boat travelled along each transect line between stations during both 1985 and 1986. Griffiths et al. (1986, p. 73-74) gives details of the locations of the 1985 transects, and Table 8 shows corresponding data for 1986. The components of the hydroacoustic system are illustrated in Figure 73. In both 1985 and 1986, the system included two side by side downward facing transducers (120 kHz, Univ. of Wash. Applied Physics Lab; 200 kHz, BioSonics) mounted in a V-fin (BioSonics Model 135). The V-fin was towed from the side of the boat, away from the wake, using armored cable. The V-fin was about 1 m below the surface. Tow speed was about 7.4 km/h in 1985 and 10.9 km/h in 1986 during surveys between stations, and about 3.6 km/h during zooplankton tows. Vertical movements of the V-fin, due to wave action, were minimized by using a bungy-cord absorption apparatus attached to the armored cable.

Results from the two echosounder frequencies were expected to be complementary. The 120 kHz echosounder was expected to detect primarily the larger zooplankters. The 200 kHz echosounder was expected to detect medium-sized as well as large zooplankters in the upper part of the water column, but to have a reduced maximum depth capacity relative to the 120 kHz system. The 200 kHz system receives a stronger return from medium-sized plankton (e.g. copepods) because of its shorter wavelength. However, depth capacity is reduced because the higher the frequency, the greater the rate of sound absorption in seawater. In practice, both echosounders were capable of sampling depths as great as 100 m during both years of the study.

When triggered by the 120 kHz echosounder, the 120 and 200 kHz transducers simultaneously transmitted sound pulses into the water column. The returning echoes for each frequency were amplified (20 log range) by the respective echosounders and sent to two chart recorders (BioSonics Model 115), the oscilloscope (Hitachi Model V222), and the recording system. The data from one frequency were also sent to the echo integrator (BioSonics Model 121) and integrated in real-time. The real-time data were saved by computer as they were collected. The chart recorder for the 200 kHz sounder produced a permanent hardcopy echogram; the signal threshold circuit in the chart recorder was adjusted to eliminate signals less than 100 mV. The oscilloscope was used to monitor echo voltages output from the echosounder.

Table 8. Summary of continuous hydroacoustic surveys, depths, surface temperatures and salinities in the Alaskan and Canadian Beaufort Seas between Barter and Herschel Islands, 4-19 September 1986. See Griffiths et al. (1986, p. 737.4) for corresponding 1985 data.

Transect Number	From Station to	Time (ADT)	Date (Day/Mo/Yr)	Location		Water Depth (m)	Temp (°C)	salinity (ppt)
A	86-1 to start of Transect B	1224	04/09/86	69°35.4'N	139°28.2'W	13.0	3.5	23.5
		1239		69°36.2'N	139°28.7'W	19.0	3.5	24.2
		1254		69°37.3'N	139°27.5'W	23.0	3.5	25.0
		1258		69°37.4'N	139°27.7'W	23.0	3.4	25.0
		1304		69°37.7'N	139°27.2'W	23.0	3.5	25.0
		1312		69°38.0'N	139°27.5'W	27.0	3.2	25.6
		1315		69°38.0'N	139°27.5'W	27.0	3.2	25.6
		1330		69°38.9'N	139°28.5'W	27.0	3.2	
B	Transect B to 86-2	1337	04/09/86	69°38.9'N	139°28.5'W	27.0	3.4	25.3
		1352		69°39.9'N	139°28.5'W	27.0	3.4	25.3
C	86-5 to start of Transect D	1629	09	69°51.2'N	141°54.6'W	16.0		22.1
		1644		69°52.3'N	141°54.0'W	20.0		22.1
		1659		69°53.9'N	141°53.3'W	22.0		25.6
		1714		69°54.5'N	141°52.6'W	25.0		25.6
D	End Transect C to 86-6	1725	05/09/86	69°54.5'N	141°52.9'W	26.0		25.6
		1740		69°54.3'N	141°50.5'W	26.0		25.6
		1755		69°54.0'N	141°48.6'W	26.0		25.3
		1810		69°53.8'N	141°45.7'W	27.0		25.3
E	86-6 to shore	1924	05/09/86	69°52.2'N	141°47.7'W	27.0		25.3
		1939		69°53.2'N	141°48.7'W	25.0		25.3
		1954		69°52.6'N	141°50.6'W	22.0		25.3
		2009		69°51.9'N	141°51.7'W	19.0		25.6
		2024		69°50.6'N	141°52.6'W	16.0		25.0
F	86-7 to 86-8	1233	06/09/86	69°49.8'N	141°52.8'W	10.0	1.9	25.6
		1248		09 50.5'N	141°50.5'W	17.0	3.8	25.3
		1303		69°51.3'N	141°50.0'W	20.0	4.4	25.6
		1318		69°52.7'N	141°47.6'W	23.0	4.2	26.3
G	86-8 to end of Transect G	1501	06/09/86	69°53.2'N	141°50.7'W	22.0	3.8	26.3
		1516		69°53.1'N	141°48.0'W	24.0	3.8	25.6
		1531		69°52.7'N	141°46.1'W	24.0	4.3	25.6
		1546		69°52.5'N	141°43.4'W	23.0	4.0	25.6
H	End Transect G to end of Transect H	1554	06/09/86	69°52.4'N	141°43.2'W	23.0	4.0	25.6
		1609		69°51.4'N	141°44.3'W	22.0	4.0	25.6
		1624		69°50.6'N	141°45.4'W	18.0	4.0	25.6
		1639		69°49.6'N	141°46.5'W	17.0	3.8	25.6
		1654		69°48.6'N	141°46.6'W	11.0	1.2	

Continued...

Table 8. Continued.

Transect Number	From Station to station	Time (ADT)	Date (Day/Mo/Yr)	Location	Water		Salinity (ppt)
					Depth (In)	Temp (°C)	
I	86-10 to 86-11	1110	07/09/86	69°37.5'N 140°46.3 'W	14.0	4.2	24.2
		1125		69°38.5'N 140°49.8'W	12.0	4.2	24.9
		1140		69°38.8'N 140°52.4'W	14.0	3.0	25.3
J	86-13 through 86-12 to hore	1728	07/09/86	69°51.5'N 141°35.0'W	25.0	2.8	24.6
		1743		69°50.3'N 141°36.1'W	24.0	3.6	24.6
		1758		69°49.0'N 141°36.3'W	20.0	3.0	24.6
		1813		69°48.0'N 141°38.5'W	14.0	2.8	21.1
		1823		69°47.2'N 141°40.8'W	10.0	0.5	21.4
4	T4-1 to T4-2	0741	10/09/86	69°41.7'N 141°15.6'W	10.0	3.5	22.8
		0756		69°43.0'N 141°14.2'W	14.5	3.8	25.6
		0811		69°44.3'N 141°12.4'W	21.0	3.8	27.0
4	T4-2 to T4-3	0947	10/09/86	69°45.4'N 141°13.2'W	23.0	3.5	27.8
		1002		69°46.7'N 141°11.0'W	26.0	3.4	27.0
		1022		69°47.3'N 141°06.8'W	31.0	3.0	26.3
		1037		69°49.1'N 141°04.4'W	31.5	2.8	26.0
		1052		69°50.3'N 141°05.3'W	33.0	4.0	25.6
		1107		69°51.8'N 141°00.1'W	37.0	4.0	26.0
		1 1 2 2		69°53.5'N 140°57.6'W	39.5	4.0	26.0
		1137		69°54.9'N 140°55.7'W	43.0	4.0	26.3
4	T4-3 to T4-4	1328	10/09/86	69°53.9'N 140°54.4'W	41.0	3.5	26.3
		1343		69°54.8'N 140°54.5'W	43.3	3.5	26.3
		1358		69°56.2'N 140°50.6'W	45.1	3.2	26.3
		1413		69°57.3'N 140°54.1'W	47.0	3.2	26.3
		1428		69°58.5'N 140°57.0'W	48.0	3.0	26.7
		1443		69°59.7'N 140°59.9'W	49.0	3.2	26.3
		1 4 5 3		70°00.6'N 140°58.5'W	49.0	3.2	26.3
		1513		70°02.4'N 140°55.8'W	51.0	3.5	26.7
		1528		70°03.7'N 140°53.9'W	53.0	3.5	26.7
		1543		70°05.1'N 140°52.5'W	53.0	3.0	25.6
		1558		70°06.9'N 140°52.9'W	53.0	3.2	25.3
4	T4-4 to T4-5	1040	11/09/86	70°07.8'N 140°52.1'W	51.0	2.8	26.3
		1055		70°09.0'N 140°50.0'W	51.0	2.8	26.0
		1 1 1 0		70°10.2'N 140°47.4'W	48.0	2.5	26.0
		1125		70°11.2'N 140°44.4'W	49.0	2.4	25.6
		1140		70°12.2'N 140°41.5'W	50.0	2.4	26.0
		1155		70°13.3'N 140°38.5'W	51.0	2.8	24.2
		1210		70°14.7'N 140°35.2'W	57.0	3.3	22.1
		1225		70°16.0'N 140°33.9'W	63.0	3.3	21.8
		1240		70°17.8'N 140°34.2'W	181.0	2.8	

Continued...

Table 8. Continued.

Transect Number	From Station to Station	Time (ADT)	Date (Day/Mo/Yr)	Location	Water Depth (m)	Temp (°c)	Salinity (ppt)
3	T3-1 to 33-2	0950	12/09/86	69°51.3'N 142 °01.2'W	11.0	3.0	26.3
		1005		69°52.2'N 141°59.6'W	18.0	2.8	26.3
		1020		69°53.9'N 141 °58.2'W	22.0	2.8	26.3
3	T3-2 to T3-3	1227	12/09/86	69°53.5'N 141 °53.4'W	23.0	3.0	26.3
		1242		69°54.4'N 141 °51.4'W	25.0	3*3	26.3
		1257		69°55.6'N 141°50.7'W	27.0	3.8	26.3
		1312		69°57.0'N 141°50.3'W	36.0	3.8	26.3
		1327		69°58.7'N 141°50.3'W	34.0	3.5	26.3
		B42		69°59.3'N 141°50.9'W	37.0	3.3	26.3
		1357		70°00.8'N 141°51.3'W	40.0	3.3	26.3
		1412		70°01.9'N 141°51.8'W	41.0	3.2	26.3
		0934	13/09/86	70°02.2'N 141°51.8'W	41.0	2.4	25.6
		70°03.1'N 141°49.9'W		42.0	2.0		
3	2'3-3 to T3-4	1151	13/09/86	70°01.5'N 141°49.4'W	42.0	2.4	25.6
		1206		70°02.7'N 141°48.9'W	41.0	2.3	25.3
		1221		70°03.9'N 141°48.1'W	46.0	2.2	25.3
		1236		70°05.2'N 141°47.7'W	47.0	1.8	25.3
		1251		70°06.4'N 141°46.7'W	49.0	1.8	25.3
		1306		70°07.9'N 141°46.7'W	50.0	1.8	25.6
		1321		70°09.2'N 141°45.9'W	51.0	1.8	25.6
		1336		70°10.4'N 141°45.5'W	51.0	1.8	25.3
		1351		70°11.6'N 141°43.2'W	52.0	1.8	25.6
		1406		70°12.9'N 141°41.9'W	53.0	1.8	2%6
3	T3-4 to T3-5	0958	14/09/86	70°12.9'N 141°42.2'W	52.0	1.8	25.3
		1013		70°14.2'N 141°40.7'W	52.0	1.8	25.3
		1028		70°15.5'N 141°39.5'W	53.0	1.8	25.3
		1043		70°16.9'N 141°39.6'W	57.0	1.8	25.3
		1058		70°17.9'N 141°38.2'W	56.0	1.8	25.3
		1113		70°19.1'N 141°36.9'W	62.0	1.8	25.3
		1128		70°20.3'N 141°35.4'W	" 65.0	1.8	25.3
		1143		70°21.4'N 141°34.3'W	70.0	1.8	25.3
		1158		70°22.9'N 141°32.6'W	109.0	1.8	25.3
		1213		70 °24.0'N 141°31.5'W	231.0	1.8	
1	T1-1 to T1-2	0937	16/09/86	70°09.4'N 143°38.6'W	12.0	1.0	26.3
		0952		70°10.8'N 143°38.6'W	19.0	1.0	26.7
		1007		70°12.2'N 143°37.7'W	24.0	0.8	27.4
		1022		70°13.5'N 143°39.1'W	34.0	1.2	27.4

Continued...

Table 8. Concluded.

Transact Number	From Station to Station	Time (ADT)	Date (Day/Mo/Yr)	Location	Water Depth (m)	Temp (°C)	Salinity (ppt)
1	T1-2 to <b>T1-3</b>	1216 1231 1246 <b>1301</b> <b>1316</b> 1331 <b>1346</b>	16/09/86	70°14.0 'N 143°036.0 'W 70°14.9 'N 143°37.1 'W 70°16.1 'N 143°036.7 'W <b>70°17.5'N 143°35.2'W</b> <b>70°18.7'N 143°33.5'W</b> 70°19.9'N 143°032.5 'W <b>70°21.3'N 143°31.8'W</b>	35.0 35.0 41.0 42.0 43.0 43.0 47.0	1.8 1.8 <b>1.8</b> <b>2.0</b> 2.0 2.2 2.0	27.4 27.0 26.3 26.0 26.0 26.0
1	T1-3 to <b>T1-4</b>	0918 0933 0948 <b>1003</b> 1018 1033 1058	17/09/86	70°21.2 'N 143°029.9 'W 70°22.7 'N 143°30.1 'W 70°24.1 'N 143°030.3 'W <b>70°25.4'N 143°029.3 'W</b> 70°26.5 'N 143°30.4'W 70°27.7 'N 143°32.6'W 70°28.8 'N 143°034.9 'W	48.0 48.0 42.0 47.0 50.0 52.0 54.0	1.9 <b>1.8</b> 1.8 102 <b>0.2</b> <b>-0.5</b> -0.5	26.0 25.6 25.6 25.3 25.6 <b>25.3</b> 25.3
1	T1-4 to <b>T1-5</b>	1250 1305 1320 1335 <b>1350</b>	17/09/86	<b>70°28.0'N 143°32.2'W</b> <b>70°29.2'N 143°33.9 'W</b> 70°30.5 'N 143°34.7 'W 70°31.03 'N 143°34.7 'W 70°33.2 'N <b>143°34.4'W</b>	55.0 56.0 54.0 62.0 <b>122.0</b>	-0.5 <b>-0.5</b> <b>-0.5</b> <b>-0.5</b> <b>-0.5</b>	25.3 25.5 <b>25.5</b> 25.5 25.6
2	T2-1 to <b>T2-2</b>	1054 <b>1109</b> 1124 1135	18/09/86	<b>70°04.4'N 142°54.3'W</b> 70°05.8 'N 142°052.1 'W 70°06.3 'N 142°50.8'W 70°07.8 'N 142°49.9'W	10.0 15.0 20.0 26.0	<b>1.2</b> 1.4 <b>2.0</b> 2.0	27.4 26.7 26.7 26.7
2	T2-2 to T2-5	1302 <b>1317</b> 1332 1347 1402 <b>1417</b> 1432 M47 1502 1517 1532 1547 1602	18/09/86	70°07.8 'N 142°48.6'W <b>70°09.0'N 142°049.3 'W</b> <b>70°09.9'N 142°50.3 'W</b> <b>70°11.0'N 142°46.4'W</b> <b>70°12.2'N 142°044.9 'W</b> 70°13.2'N 142°44.1 'W <b>70°14.4'N 142°42.9 'W</b> 70°15.7 'N 142°41.8 'W 70°17.4'N 142°040.5 'W 70°18.3 'N 142°039.5 'W 70°19.6 'N 142°38.3'W 70°20.9 'N 142°37.0'W <b>70°22.3'N 142°36.0'W</b>	25.0 30.0 35.0 <b>33.0</b> <b>40.0</b> <b>44.0</b> 41.0 47.0 46.0 52.0 56.0 57.0 60.0	2.0 2.3 2.5 2.5 <b>2.5</b> 2.5 2.5 2.3 <b>2.0</b> 2.0 2.0 2.0 0.8	27.4 26.3 26.0 25.6 25.6 25.6 25.6 25.6 26.0 26.0 26.3 26.0
2	T2-2 to <b>T2-5</b>	1034 1049 <b>1104</b> <b>1119</b> 1134 1149 1204 <b>1219</b> <b>1234</b> <b>1238</b>	19/09/86	70°22.3'N 142°35.9 'W <b>70°22.3'N 142°31.4'W</b> <b>70°23.9'N 142°30.4'W</b> <b>70°25.0'N 142°32.5 'W</b> <b>70°26.2'N 142°32.1 'W</b> <b>70°27.4'N 142°31.3 'W</b> <b>70°28.6'N 142°29.9 'W</b> <b>70°30.0'N 142°28.8 'W</b> 70°31.2'N 142°28.2 'W 70°31.5'N 142°27.5 'W	58.0 58.0 60.0 61.0 <b>61.0</b> 63.0 <b>64.0</b> 66.0 110.0 150.0	0.5 <b>-0.3</b> <b>1.2</b> 1.2 1.2 <b>1.2</b> <b>1.2</b> <b>1.2</b> 2.0 2.0	

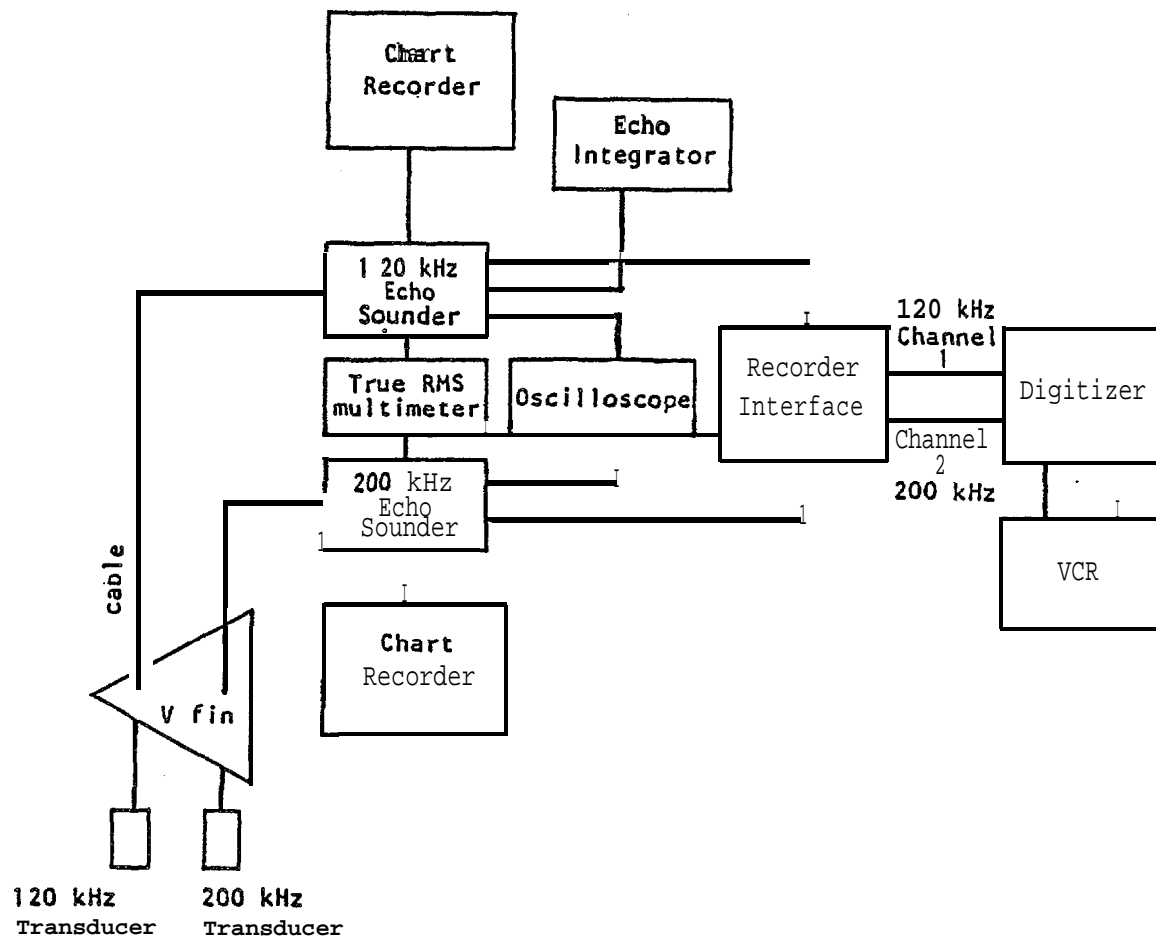


FIGURE 73. Block diagram of the hydroacoustic data collection system used in the Eastern Alaskan Beaufort Sea, September 1985. The system was the same in 1986, except that the 200 kHz data were echo integrated in real time.

The recording system digitized and encoded the signals on video tape. The recording system consisted of a recorder interface, **BioSonics** Model 171; a digital processor, Sony Model **PCM-F1**; video cassette recorder, Sony Model **SL-HF-300**; and a **multimeter**, Fluke Model 27. The echo integrator was used to obtain real-time data on relative biomass at various depths and times (= locations). Acoustic data recorded on the VCR were **re-analyzed** through the integrator in the laboratory after the field season; these were the primary acoustic data used in both years of the study.

### Temperature and Salinity

Profiles.--In September of both 1985 and 1986, continuous temperature and salinity profiles from the surface to bottom were measured at each zooplankton station using an Applied Microsystems **CTD-12**. Additional profiles were taken during 1986 in areas where we sampled among bowhead whales. All data were recorded on a self-contained **tape** recording unit (see 'Water Masses' section, p. 41-45)

Continuous Surface Measurements.--In 1985, during surveys between stations, near-surface temperature ( $\pm 0.2^{\circ}\text{C}$ ) and conductivity ( $\pm 2.0$  millimhos/cm), along with water depth, were determined every 15 min (see **Griffiths et al.** 1986, p. 73-74, for data). Temperature and conductivity values were obtained with a **Hydrolab** System 4000 from surface water samples. Conductivity readings were converted to salinity values by Arctic Sciences Ltd. (see 'Water Masses' section, p. 38-43). In September 1986, a continuous record of near-surface temperatures was made during transects between stations. Temperatures were obtained using a **Hydrolab TC-2 (TCOSL)** and were recorded on a chart recorder (**SolTech** Model 6723). Conductivity was obtained from the same **Hydrolab TC-2** every 15 min; the values were later converted to salinities by Arctic Sciences Ltd. (Table 8). During both years, depths were determined from the **hydroacoustic** system.

### Water and Chlorophyll Sampling

Hydro Casts.--At each of the five stations on Transect 2 in 1985 and the five stations on Transect T3 in 1986, water samples for nutrient analyses were collected at 5 m intervals from the surface to a depth of 20 m; at 10 m intervals at depths 20 to 50 m; and at additional depths of 100, 150 and 175 m at the deepest station in 1985 and 100, 150 and 200 m at the deepest station in 1986. All nutrient samples were filtered, preserved with three drops of 2% **HgCl<sub>2</sub>**, and stored, unfrozen.

Usable chlorophyll samples were not obtained in 1985. In 1986, 11 chlorophyll samples were collected at the five stations along Transect T3 (2 samples from Stations **T3-1** to **T3-4** and three from Station **T3-5**) from the same casts as the water samples. For each sample, 1000 mL of water were filtered through **Gelman** glass fiber filters and 10 mL of a saturated solution of **MgCO<sub>3</sub>** was added to the last of the water being filtered. The filters were then folded, placed in **glycine** envelopes, and frozen inside **whirlpacs**. These samples were sent to the University of Alaska, Fairbanks, for analysis.



Continuous Surface Chlorophyll. --In September of 1985 and 1986, an aliquot of the surface water sample collected every 15 min was read on a fluorometer to estimate its chlorophyll content. Chlorophyll samples (see 'Hydro Casts' , above) were used to calibrate the instrument.

Turbidity Samples. --In September 1986, surface turbidity samples were taken at each zooplankton station along the four broad-scale survey transects and at stations 86-9 through 86-13. A 125 mL aliquot of water was collected at each station and was preserved by adding 2-3 drops of  $\text{HgCl}_2$ . The samples were returned to the laboratory and read on a HACH Turbidimeter (Model 16800). In addition, secchi disc readings were taken at all stations during the 1986 season and at stations 6-13 in 1985.

### Laboratory Analyses

Zooplankton. --All samples from both years were sieved through a 0.25 mm mesh nylon screen, washed with water, and examined under a low-power binocular microscope. In 1985, individual organisms from all samples were identified to species where possible, counted, and wet-weighed by species to the nearest mg using a Mettler PT 200 electronic balance. In 1986, due to the large number of samples collected and analysis time constraints, only samples from the oblique, vertical and a few selected horizontal tows were identified to species and counted. However, samples from the other horizontal tows from 1986 were analyzed by major taxonomic group (e.g. copepods, amphipods, euphausiids, etc.); wet-weights by taxonomic group were obtained using the Mettler PT 200 balance. In this way total biomass for each horizontal tow sample was determined for comparison with the hydroacoustic results. Between-year differences in species composition were determined from the oblique tow samples.

In both 1985 and 1986, if large numbers of individuals were present, the sample was first scanned for large or rare organisms and then sub-sampled with a Folsom Plankton Splitter (McEwen et al. 1954). In practice, copepods were the only group for which subsampling was necessary. In these cases, copepods in the subsample were counted, weighed to the nearest mg, and identified to species and life-stage. The subsample data were then applied to the whole sample to estimate total numbers and wet weight for each species and life-stage of copepod in the sample. Cephalothorax lengths of approximately 10-20 undamaged individuals of each copepod species and life-stage, from 1985 samples, were measured to the nearest mm and weighed to the nearest mg to determine sizes and weights of individual zooplankters.

In both years, wet-weight data from oblique tows were used to calculate the biomass/m<sup>3</sup> for zooplankton in the water column as a whole. Data from the horizontal tows were used to calculate wet-weight biomass at particular depths. For each sample, the flowmeter reading was used to calculate the volume of water filtered. This information, in conjunction with the weight of the sample, was used to determine the total biomass in mg/m<sup>3</sup>.

In 1985, individuals from the major groups of large organisms (e.g. amphipods, euphausiids, mysids, fish larvae etc.) taken in the Tucker trawls and associated bongo tows were counted, and those in good condition were measured to the nearest mm. Numerical and size data from the two types of nets

were then compared. Because of **the** large mesh size of the Tucker trawl (6.4 mm), only the large species and size classes were considered.

Calorimetric Determinations.--In both years, selected **zooplankton** samples were frozen in the field and returned to the Institute of Marine Science, University of Alaska, for caloric analysis. In 1985, each sample consisted of the **zooplankton** from one side of a bongo tow frozen in a single **whirlpac**. In 1986, two types of samples were collected. Those taken on the 'Annika Marie' in September were unsorted and comparable to the 1985 samples. Those taken on the 'Polar Star' in October were separated into major taxonomic groups and size classes on the ship and then frozen separately.

The large composite samples from September of both years were allowed to thaw and the major components (**e.g. copepods, amphipods, euphausiids**, etc.) were immediately separated. Copepods were further separated into large (>1.8 mm) and **small** (<1.8 mm) categories. Since freezing and thawing can cause cell **lysis** and a consequent **loss** of body fluid, care was taken to **select** turgid and minimally damaged individuals when possible.

All samples were then dried to a constant weight and individually ground to a powder. Caloric content was determined with a Parr adiabatic bomb calorimeter using samples of 0.3 to 1.0 grams. When tows did not contain sufficient numbers of particular organisms to provide enough material for analysis, **samples** from adjacent stations were pooled. Results are reported as calories per gram dry weight (**one** calorie = **4.18** Joules).

Ash content of **zooplankton** samples was obtained 'by weighing a **subsample** onto a platinum pan and **combusting** slowly in a 'covered porcelain crucible. The temperature was raised to **600°C** over 3 h and maintained at **600°C** for 1 h. The samples were then allowed to cool **slowly** to room temperature, removed from the furnace, and weighed.

#### Data Processing and Analysis

Zooplankton Data.--Results from the laboratory analyses of **zooplankton** were entered into an IBM PC-AT microcomputer and standardized to **number/m<sup>3</sup>** and **biomass/m<sup>3</sup>** in 1985 and **biomass/m<sup>3</sup>** in 1986. These data were analyzed on the PC-AT computer using programs written for this project, **BMDP** and **Lotus 1-2-3**. Additional analyses were run on the 1986 data using a Macintosh Plus microcomputer with **StatView 512+** and **Excel** software.

Hydroacoustic Data.--In both years, hydroacoustic data were obtained by reproducing voltages recorded on VCR tape during data collection, and processing them with the echo integrator. Echo integration is a process whereby the signals received by the echosounder from selected depth intervals are squared and averaged over selected time periods. During the two years of this study, **the** system did not process signals below the measured background noise level. In 1985, depth strata were 2 m thick for depths between 4 and 52 m, and 10 m thick between 52 and 102 m. In 1986, integrator depth strata were 1 m thick for depths between 3.5 and 56 m, and 5 m thick between 56 and 101 m.

In both years, a measure proportional to average zooplankton biomass within a stratum of specific thickness was obtained by averaging the corresponding squared voltages out of the echosounder within every 2-minute period. Echo integration is based on the principle that echo intensity is proportional to the target biomass. The product of the mean squared voltage and a constant A gives volume scattering (VS), the primary data for the study. The volume scattering data are directly proportional to zooplankton biomass under ideal conditions:

$$VS = (A) (\text{mean } V^2)$$

$$A = (\pi \tau c \sigma_{bs} P_o^2 g^2 b^2(av))^{-1}$$

where

$$\pi = 3.142$$

$$\tau = \text{pulse width (s)}$$

$$c = \text{speed of sound in water (m/s)}$$

$$\sigma_{bs} = \text{mean backscattering cross sectional area per unit biomass (m}^2\text{)}$$

$$P_o^2 = \text{transmit pressure level at 1 m from transducer (microPascals)}$$

$$g^2 = \text{the fixed through system gain (V/microPascal)}$$

$$b^2(av) = \text{mean squared beam pattern weighting factor (dimensionless)}.$$

Mean backscattering cross section (sigma) of zooplankton during the study was unknown and was set equal to one. The A constants with sigma equal to one for the 120 kHz data were  $2.084 \times 10^{-6}$  and  $2.474 \times 10^{-7}$  in 1985 and 1986, respectively; for 200 kHz data they were  $1.176 \times 10^{-6}$  and  $2.390 \times 10^{-7}$  for 1985 and 1986, respectively. After scaling for these A-constants, data for the 120 and the 200 kHz systems were directly comparable.

Since the backscattering cross section per unit biomass was not known, the volume scattering data represent only relative biomass. To convert to an estimate of absolute biomass, a regression relationship between volume scattering and biomass/m<sup>3</sup> was determined based on horizontal bongo tows conducted simultaneously with echosounding (see 'Acoustic Biomass vs. Net Biomass', p. 169-170).

Processing of the hydroacoustic data differed between 1985 and 1986. In 1985, the raw VS data were strongly correlated with net biomass at the same locations. In 1986, the raw VS data were not nearly as well correlated with the net data, and additional processing was necessary. The presence of numerous large fish (>50 mm in length) in 1986 biased the correlation between volume scatter and net biomass in that year. These fish could readily avoid capture in the plankton nets but gave strong echo returns. To overcome this problem, the 1986 data from the 200 kHz sounder were echo integrated separately at two different threshold levels. The lower threshold level was set just above the level of the ambient noise (40 mV for the 0 to 10 m stratum) and was increased 10 mV for each 10 m depth increment because the level of background noise increases with depth. The upper level was set at 800 mV; the echoes stronger than this were presumed to be from fish and not zooplankton. The volume scatter data obtained using the higher threshold level were subtracted from those using the lower threshold level to estimate backscattering by zooplankton. Although this procedure substantially reduced the biasing effect of fish in the 1986 analysis, it could not eliminate them completely. For example, echo returns from fish located off the acoustic axis

could be below the upper threshold level and thus be included. Unless otherwise stated, VS data for 1986 used in this report were obtained by this procedure. A similar analysis was not performed on the 120 kHz data from 1986 since they tended to underestimate the contribution of the smaller zooplankters (i.e. copepods); the 120 kHz data were not used in our analyses.

### Results

The results presented below are based on the zooplankton samples, acoustic sampling, and physical and chemical measurements taken during September 1985 and 1986 in and near the official study area, supplemented by the zooplankton samples and physical measurements taken over a broader area during the October 1986 'Polar Star' cruise.

### Validation of Sampling Methods

Bongo vs. Tucker Net Tows. --To assess whether large and fast-swimming zooplankters such as large amphipods and euphausiids were underestimated in bongo net tows, a modified Tucker trawl was used to collect additional samples at the same locations as selected bongo tows. This large mesh trawl was designed to be towed without a bridle, to minimize the avoidance reactions of macroplankton. The Tucker trawl is an effective sampler of large zooplankton and small fish (Sameoto and Jaroszynski 1976). However, all types of zooplankton sampling gear have inherent biases, and all probably underestimate the actual densities present (e.g. Wiebe et al. 1982). Overall densities of animals collected with the bongo and Tucker trawl are not comparable because the mesh opening in the Tucker trawl is about 13 times larger than that of the bongo net (6.4 mm vs. 0.5 mm). Thus, small animals are not expected to be collected by the Tucker trawl. Instead, we determined whether larger animals were collected by the Tucker trawl, and compared the apparent densities of large animals as determined by the two gear types.

The results showed that both bongo nets and Tucker trawls collected a wide range of sizes of all major groups of macrozooplankton (e.g. amphipods, mysids and euphausiids; Griffiths et al. 1986). Also, on a per unit volume basis the bongo net was more efficient than the Tucker trawl in capturing large individuals. All size classes captured in the Tucker trawl were represented in the bongo net samples. Thus, the results from the Tucker trawl did not indicate the need for any correction factor for large animals that might be undersampled by the bongo nets (Griffiths et al. 1986, p. 79-83).

Depth of Bongo Nets. --In all 1985 and most 1986 horizontal tows, depths of the bongo apparatus were determined from the attached Apelco depth sounding system. However, in 1986, stations 86-1 through 86-13 were sampled prior to the Apelco system becoming operational. In these cases, horizontal sample depths were calculated from wire angle measurements and the amount of wire out. Once the Apelco system became operational in 1986, we continued to record wire angle and amount of wire out so that the two methods could be compared. There was a strong positive relationship ( $r = 0.99$ ;  $P < 0.001$ ;  $n = 36$ ). The fit appeared to be best for the depth range 0 to 25 m (Fig. 74), which corresponded to the range of sampling depths at stations where the 'wire angle and amount of wire out' method was used. Thus calculated depth values were sufficiently accurate to allow the inclusion of the horizontal tows taken at

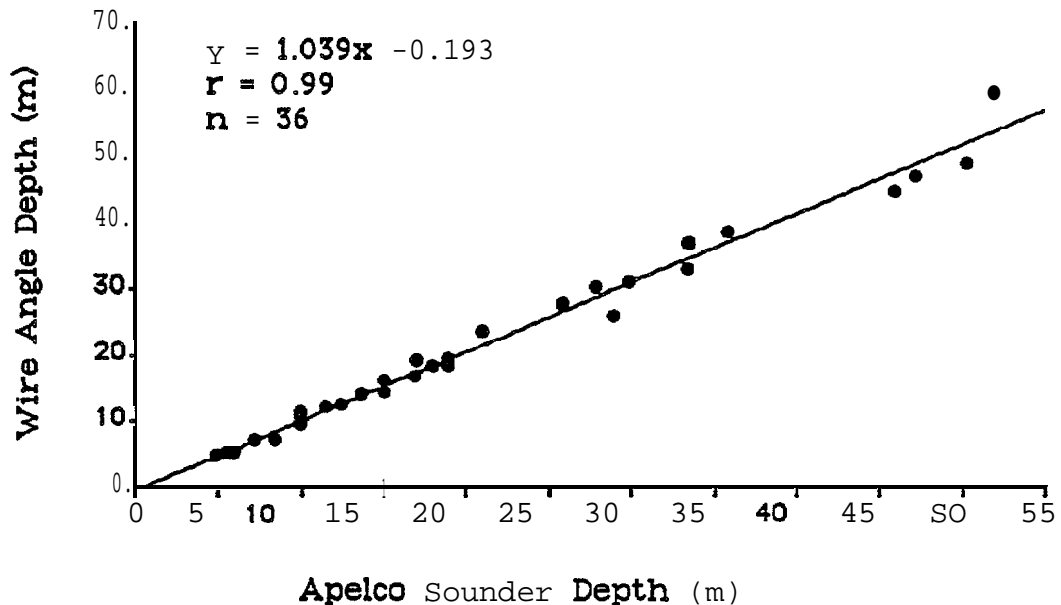


FIGURE 74. Comparison of sample depth using wire angle depth vs. Apelco sounder depth.

stations 86-1 through 86-13 in the analysis of zooplankton biomass vs. hydro-acoustic return.

Standard vs. Opening-Closing Bongo Nets.--In 1985, the primary zooplankton sampling device was a standard bongo net. Because this net sampled during both descent and ascent, the values obtained during horizontal tows were somewhat biased (Griffiths et al. 1986) and not ideal estimates of zooplankton biomass at the depths that were nominally sampled. To eliminate this bias during the 1986 sampling program, we used an opening and closing bongo net that collected the entire sample at the desired depth. However, some other types of sampling were conducted using the standard bongo net during September 1986 in this study, during the 'Polar Star' cruise of October 1986, and in a 1985-86 study of zooplankton in the Canadian Beaufort Sea (Bradstreet and Fissel 1986; Bradstreet et al. 1987). To compare the sampling efficiencies of the two types of bongo assemblies we compared samples collected in a single area by the two types of bongo nets.

The comparisons were based on samples from five replicate oblique tows collected with each type of net at one station on 15 September 1986. Double oblique tows rather than horizontal tows were used in the comparison because, with the double oblique technique, both nets sampled during the descent-ascent cycle. In addition, the difficulties of collecting 10 horizontal tows within

the same **zooplankton** layer over an extended period of time were eliminated. In order to standardize the **zooplankton** available during the tows as much as possible, sampling was carried out while **steaming** back and forth over the same area. As a further check on the consistency of the **zooplankton** present during each tow, the **hydroacoustic** system was used during each tow to measure the amount of **zooplankton** present.

Calculated **biomasses** of all major **zooplankton** groups (and total biomass) were higher based on samples collected with the standard bongo net (Table 9). Mean values from standard bongos ranged from 1.23 to 5.82 times those from the opening and closing **bongos**, depending on the **taxonomic** group. **Except** for fish larvae, amphipods and **detritus**, the differences between the gear types were significant (Table 9). These differences did not appear to be related to the **volume of** water sampled (no significant difference between nets;  $t = 1.583$ ,  $p = 0.165$ ,  $df = 8$ ). The differences also were not the result of any differences in the **total** amount of **zooplankton** in the water column at **places** where the **two** types of samples were collected (no significant differences for the 200 kHz or 120 kHz volume backscatter during the tows of the two gear types; Table 9). The **echosounder** data do not rule out the possibility that there may have been some differences in the group composition of zooplankton between sampling locations. However, it is more **likely** that the differences in apparent biomass were related to the towing configuration of the two net types. In the standard bongo assembly, the bongo frame is **attached** to **the hydrocable** and towed so that no gear precedes the net entrance. This minimizes the possibility of avoidance due to a pressure wave in front of the net. In the case of the opening and closing net, the closing device and associated lines have to be towed in front of the net. This configuration would tend to deflect some portion of the **zooplankton**. In addition, the flow of water around the leading edges of the opening and closing nets would be more turbulent than around the standard nets; in the former case, the nets were tied to **the** rings with **line**, whereas **in** the latter case they were clamped to the standard frame. The increased turbulence would be expected to reduce the efficiency of the opening and closing nets and result in **lower** catches.

These factors **could** account for the differences in apparent **zooplankton** biomass as determined by the two types of net. It was surprising that differences for the more **motile** organisms (fish larvae and amphipods) were **not** significant, given their abilities to sense pressure variations and move rapidly. It is possible that their distribution patterns were more patchy than those of the other zooplankton groups, thus increasing the variance within each net type and reducing statistical significance levels.

The **zooplankton biomasses** determined from the opening and closing bongo nets in 1986 were corrected, i.e. **scaled** upward, by applying the appropriate correction factor from Table 9 to each group and to the 'total-detritus biomass' group. Two correction procedures were followed, depending on circumstances. Method 1: When analyzing the 1986 **hydroacoustic** data vs. net biomass, the corrected 'total-detritus biomass' was used because the **hydroacoustic** system was unable to distinguish among zooplankton groups, and because the **resulting** relationship was to be applied over large areas where the group composition of the zooplankton community was not known. Method 2: For comparisons of net **biomasses** among stations or areas, correction factors for each **zooplankton** group were applied and these converted **values** were summed

**Table 9.** Correction factors applied to the major zooplankton groups collected in the opening and closing bongo net. Based on comparisons with samples collected by a standard bongo net towed in the same way at the same station and date. Five samples from each net type are used in the comparisons. The **t**-tests were modified for unequal variances (**t'**-test).

Group	Biomass (mg/m <sup>3</sup> )		t' (df)	2-tail pa	Correction Factor
	Mean	SD			
<b>Total Biomass</b>					
Standard Net	26.01	5.39	4.72	**	2.05
Open-Close	12.66	3.30	(7.9)		
Total - Detritus					
Standard Net	21.12	8.69	2.49	*	1.94
Open-Close	10.87	3.09	(5.5)		
<b>Copepods</b>					
Standard Net	2.15	1.05	2.44	*	2.53
Open-Close	0.85	0.56	(7.2)		
<b>Pteropods</b>					
Standard Net	1.45	0.67	3.58	*	4.53
Open-Close	0.32	0.22	(5.3)		
<b>Amphipods</b>					
Standard Net	3.64	0.94	0.92	ns	1.23
Open-Close	2.95	1.38	(8.6)		
Fish Larvae					
Standard Net	7.83	7.14	0.67	ns	1.41
Open-Close	5.55	2.62	(5.6)		
<b>Hydrozoans</b>					
Standard Net	1.31	0.61	3.31	*	3.36
Open-Close	0.39	0.12	(4.5)		

Continued...

Table 9. Concluded.

Group	Biomass (mg/m <sup>3</sup> )		t' (df)	2-tail p <sup>a</sup>	Correction Factor
	Mean	SD			
<b>Decapods</b>					
Standard Net	4.54	1.28	5.14	***	5.82
Open-Close	0.78	1.02	(9.4)		
Detritus					
Standard Net	4.84	4.66	1.46	ns	2.72
Open-Close	1.78	0.61	(4.2)		
<b>Mysids</b>					1.32 <sup>b</sup>
<b>Euphausiids</b>					1.32 <sup>b</sup>
<b>Chaetognaths</b>					1.32 <sup>b</sup>
<b>Volume Sampled (m<sup>3</sup>)</b>					
Standard Net	147.66	5.31	1.53	ns	
Open-Close	152.52	4.73	(9.8)		
<b>200 kHz Volume Scatter</b>					
Standard Net	2.761	0.69	1.04	ns	
Open-Close	2.389	0.41	(7.8)		
<b>120 kHz Volume Scatter</b>					
Standard Net	1.088	0.28	1.04	" ns	
Open-Close	0.953	0.08	(5.0)		

<sup>a</sup> \* 0.05 > p > 0.01; -- 0.01 > p > 0.001; \*\*\* p < 0.001; ns p > 0.01.

<sup>b</sup> These values are a mean of the fish larvae and amphipod factors (see text).



to obtain a corrected 'total-detritus biomass' for the sample. In cases where no group correction factors could be calculated due to insufficiency data (mysids, euphausiids, chaetognaths), we used the mean of the correction factors for groups that were similar in behavior, in this case the factors for fish larvae and amphipods.

Method 2 tended to give slightly higher estimates of 'total-detritus biomass' than did Method 1. A further correction was applied to make the data from the 1986 horizontal net tows at depth (where Method 2 was applied) more comparable with results from the hydroacoustic data (based on Method 1). For each sample, the 'total-detritus biomass' was determined by both Methods, and the ratio of the Method 1 : Method 2 results was determined. The calculated value for each zooplankton group was then multiplied by this ratio. After this procedure, the sum of the corrected biomasses for all taxa equalled 'total-detritus biomass' derived from Method 1. This procedure may tend to underestimate the biomasses of some individual taxa and thus it produces a conservative estimate of the corrected biomass.

Thus, horizontal tows collected with the opening-closing bongo assembly have the advantage of coming from a single depth, but have the disadvantage of underrepresenting the amount of zooplankton present. The correction procedure developed here allowed us to compensate, at least roughly, for the underrepresentation problem. These correction procedures were needed only for the samples collected by the opening and closing bongo nets, i.e. for the horizontal tows at depth during September 1986. All other bongo tows were with the standard bongo assembly (see 'Methods' section), and were not adjusted in this way. Appendix 2 shows the raw as well as the corrected results for the opening and closing bongo nets.

#### Acoustic Biomass vs. Net Biomass

The hydroacoustic -surveys provided data on zooplankton biomass at far more locations and depths than net-sampling methods. However, before the hydroacoustic data could be interpreted, it was necessary to determine the relationship of the hydroacoustic results to the zooplankton biomass as estimated by traditional net sampling. It should be noted that the V-fin carrying the transducers was towed approximately 1 m below the surface. This, coupled with turbulence in the surface waters, prevented any meaningful acoustic results from being obtained in the top 2-3 m of the water column.

1985 Relationship. --In 1985, a total of 31 horizontal bongo tows were performed, and echosounder data were obtained during 25 of these sampling periods. Of these, 8 were excluded from our analysis because of pycnocline bias (for details and data, see Griffiths et al. 1986, p. 108). The remaining 17 were used to determine the relationship of the 200 kHz echosounder results to zooplankton biomass as estimated from net tows. The following geometric mean regression (Ricker 1973, 1984) was derived:

$$\text{Biomass (mg/m}^3\text{)} = 27.85 + (346.39)(\text{volume scatter} \times 10^8)$$

( $r = 0.81$ ,  $df = 15$ , 1-sided  $p < 0.001$ ; Griffiths et al. 1986, p. 109-110). This relationship was used to estimate zooplankton biomass from echosounder data obtained along the 1985 transects.

**1986 Relationship.**--In 1986, the corrected '**total-detritus biomass**' calculated by Method 1, as described above (p. 166-9), was available" from 66 horizontal opening and closing bongo tows during which echosounder data had been collected. The **echosounder** data were processed to exclude strong echoes, believed to be **mainly** from fish (see 'Methods', p. 163-4). These data were used to determine the relationship between volume scattering and net **biomass/m<sup>3</sup>**. As in 1985, some pairs of concurrent net and **hydroacoustic** data were excluded because of problems with sharp density gradients (**pycnoclines**), particularly at stations with a layer of Bering Sea Water (see 'Water Masses' section, p. 102). In 1986, 10 of the 66 data points were excluded because of **pycnocline** bias. The excluded cases were Station 86-13, tow depth 8 m; **T4-5**, 30 m; **T3-5**, 28 and 30 m; **T1-1**, 5 m; **T1-4**, 34 m; **T1-5**, 15 and 47 m; **T2-5**, 10 and 50 m (see Fig. 69, 70, p. 141-2, for station locations).

The acoustic data used were those that corresponded to the tow depth of the bongo net. The horizontal tow depths varied slightly during each tow because of wave action and variable boat **speeds**. Hence, we averaged the volume scattering measurements (**VS**) for 2 m above and below the tow depth. For example when tow depth was 10 m, the scaled VS data for 8-12 m were averaged, For tows deeper than 56 m, where VS strata were 5 m thick, we used the VS data from the stratum **that** included the tow depth.

Both the volume scattering data and net biomass (**mg/m<sup>3</sup>**) were log transformed to stabilize the variation across the ranges of the two variables. There was a significant **simple** correlation between net biomass and VS ( $r = 0.62$ ,  $p < 0.001$ ; Fig. 75), but **the best-fit** equation was a multiple regression based on log 200 kHz volume scattering and station depth (m):

$$\text{Log (mg/m}^3\text{)} = 11.5893 + 1.0793(\text{log VS at 200 kHz}) - 0.007 (\text{Sta. depth in m})$$

( $R = 0.66$ ,  $df = 53$ ,  $p < 0.001$ ; Table 10). Tow depth was **also** considered as a possible predictor variable, but it did not account for significant additional variance after VS and station depth had been taken into account. The above equation was used to estimate zooplankton biomass from the **echosounder** results acquired at individual stations and during continuous **hydroacoustic** surveys. These **estimates** of 'acoustic biomass' were then used to determine the amount of food available to bowheads in the study area and to investigate the vertical and horizontal patchiness of **zooplankton**.

**Vertical Distributions.**--The vertical distributions of **zooplankton** in the region were examined by analysis of volume scattering data from various depths at stations with **zooplankton** tows. The VS data acquired during **all** tows at each station were averaged and then converted to estimated biomass (**mg/m<sup>3</sup>**) using the above geometric mean (1985) or multiple (1986) regression relationship. Depth layers **that** included **pycnoclines** were excluded in both years.

**Horizontal Distributions.**--Although most broad-scale horizontal transects were **disjointed** in time, i.e. conducted over 2 or more days, all data from a given transect were combined for the analysis. Horizontal distributions of **zooplankton** along each transect were investigated by averaging the **zooplankton**

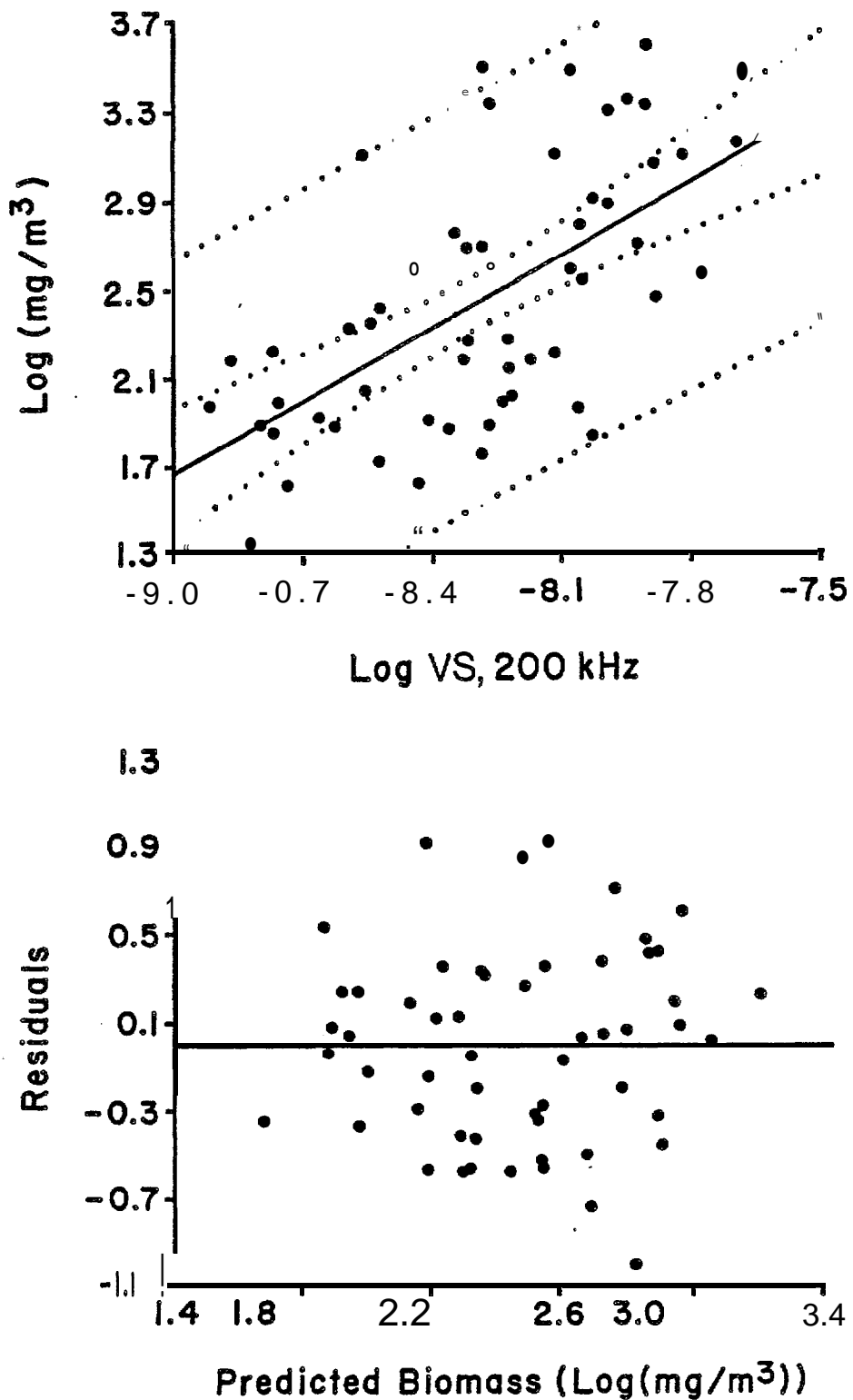


FIGURE 75\* Zooplankton biomass in horizontal tows (Log mg/m<sup>3</sup>) vs. volume scattering at 200 kHz (Log VS, 200 kHz) from corresponding locations and depths. 95% confidence limits and prediction limits for new observations are shown as dotted lines.

**Table 10.** Multiple regression of zooplankton net catch ( $\log \text{mg/m}^3$ ) on acoustic volume scattering ( $\log \text{VS}$  for 200 kHz sounder) and Station depth (m).

Independent Variable	Coefficient	Std Error	t-value	P value
Constant	11.5893	1.5095	7.68	<<0.001
Log (VS 200 kHz)	<b>1.0793</b>	0.1821	5.92	<<0.001
Sta. Depth (m)	-0.007	0.0032	-2.19	0.033
Multiple Correlation Coefficient R = 0.66      n = 56				
R <sup>2</sup> (% variance explained) =		0.44	df = 53	
R <sup>2</sup> adjusted for df		0.42		

biomass ( $\text{mg/m}^3$ ) in the entire water column for each 2-rein segment of transect. At a typical boat speed of 7.4 km/h in 1985 and 10.9 km/h in 1986, a 2-rein segment represented about 250 and 365 m of transect in 1985 and 1986, respectively. For each 2-rein period the Volume Scatter (VS) data collected from various depth strata were weighted by stratum thickness and averaged. The average VS value for the 2-rein period was then converted to estimated biomass using the regression equations developed above. In 1986, depth layers along transects affected by **pycnoclines** were excluded from the above analysis (Table 11). In 1985, all data at or above the **pycnoclines** were excluded.

**Table 11.** Depth layers along 1986 hydroacoustic transects excluded from analysis because of **pycnoclines**.

Transect	Date	Time (ADT)	Depth Layer (m)
A	9/4	12:24-13:04	3.5-7
J	9/7	17:28-17:58	6-10
1	9/16	09:37-09:52	3.5-7
1	9/17	12:50-13:50	22-35
1	9/17	12:50-13:50	45-48
2	9/19	12:04-12:38	8-12
2	9/19	12:04-12:38	48-52
3	9/14	11:43-12:13	26-32
4	9/11	12:25-12:40	28-30
4	9/11	12:25-12:40	51-55

**Zooplankton Patchiness.**--The volume scattering data acquired from the 200 kHz system during the broad-scale surveys and fine-scale transects near whales were used to assess zooplankton patchiness. For each transect, a matrix of estimated biomasses in 2-m depth strata and 2-rein (about 250 m) positional strata for 1985, and in 1-m depth strata and 2-rein (about 365 m) positional

strata for 1986 was developed. Patchiness data for each transect are presented as contour **plots** of estimated biomass versus depth "arid position along the transect. The data are presented as continuous, although those from most broad-scale transects were collected over 2-3 days. In both years, depths were corrected for transducer depth and **pycnocline** layers were excluded.

**Zooplankton vs. Water Masses and Depth, Official Study Area,**  
**September 1985-86**

**Characterization of Stations by Water Masses.** --As described under 'Present State of Knowledge', p. 136-9, a relationship has been demonstrated between the composition of arctic **zooplankton** and physical conditions, notably temperature and salinity. In 1985-86, Temperature-salinity (T/S) data from CTD profiles and surface readings were used to delineate major water masses in the Eastern Alaskan Beaufort Sea (see 'Water Masses', p. 84-102, for details). Most stations have been grouped by temperature-salinity characteristics into **three** zones based on the water masses present: nearshore, inner shelf and outer shelf (**Table 12**). Stations on 1985 Transect 4 were excluded because they were sampled after an extended period of **strong** northwesterly winds had thoroughly mixed the water masses (**Griffiths et al.** 1986).

The extent and depth ranges of the three zones varied within and between **the** two years. For example, three of the control stations (depths 23-27 m) were in the 'Inner **Shelf**' zone in early September 1986; when the broad-scale transects were sampled in mid September 1986, stations in this zone had a depth range of 41-47 m. These variations in the locations of water masses and zones should be kept in mind when interpreting the **results**.

In the following analyses, **zooplankton** data from 1986 are emphasized and comparisons are made with the 1985 data; detailed analyses of the 1985 results are provided in **Griffiths et al.** (1986). **Zooplankton** results in this subsection are from the broad-scale transects over the continental **shelf within** our official study area during September of 1985 and 1986. **Later** subsections present results from the more extensive transects during the 'Polar Star' cruise, and from whale feeding and control stations. Data concerning the major groups and species of **zooplankton** in these three situations are presented in Appendix 1. Additionally, in the case of horizontal tow samples collected with the opening and closing bongo nets in 1986, the untransformed and transformed data are presented in Appendix 2.

**Zooplankton data** from the broad-scale transects are presented in relation to the three zones listed in Table 12, "i.e. nearshore, inner shelf and outer shelf. Within each zone, the major groups are described for four situations: (1) the water **column** as a whole, (2) above the **pycnocline**, (3) within the **pycnocline** layer, and (4) below the **pycnocline** in Arctic Water or Bering Sea Water. In addition, the major species of **zooplankters** are described for the water column as a **whole**. The data are summarized in Figures 76 and 77 for 1986 and Figure 78 for 1985.

**Table 12.** Summary of stations in each of three zones during September 1985 and 1986.

Year	Transect	Nearshore	Inner Shelf	Outer Shelf
1985	Transect 1	Sta. 1	<b>Sta. 2 and 3</b>	<b>Sta. 4 and 5</b>
	Transect 2		Sta. 6a, <b>7</b> and 8	Sta. 9 and 10
	Transect 4	Water mass characteristics different (see text)		
<b>1986</b>	Transect <b>T1</b>	<b>Sta. T1-1, T1-2</b>	<b>Sta. T1-3</b>	Sta. <b>T1-4, T1-5</b>
	Transect T2	Sta. <b>T2-1, T2-2</b>		Sta. T2-5
	Transect T3	Sta. <b>T3-1, T3-2</b>	<b>Sta. T3-3</b>	Sta. <b>T3-4, T3-5</b>
	Transect T4	Sta. <b>T4-1, T4-2</b>	Sta. T4-3	<b>Sta. T4-4, T4-5</b>
1986	Whale Feeding Stations	Sta. 86-1, 86-5, 86-7, 86-9, <b>86-10, 86-12</b>		
1986	Control Stations	Sta. 86-2, 86-11	Sta. 86-6, 86-8, 86-13	

<sup>a</sup> Ice prevented zooplankton sampling at 1985 station 6.

**Nearshore Waters.**--In 1985, **only** a single station, at a water depth of 13 m, was located in this zone (Table 12). Temperatures and salinities were nearly uniform from surface to bottom and the temperature was 1 Co greater (i.e. **0.15°C**) than expected given-the salinity of 31 **psu**. In 1986, the nearshore" water was different in characteristics; a more extensive zone extending up to 15 km from shore is treated here as 'nearshore'. It contained eight of the transect stations (water. depths 10 to 34 m), all whale feeding stations, and two control **.stations** (water depths 12 to 25 m; Table 12). Surface temperatures were considerably higher than in 1985, reaching maxima of **3.4 to 4.5°C**. Salinities were approximately 1.5 to 2 **psu lower** than in 1985. At depth, there was little evidence of Arctic Water (AW, = Arctic Surface Water) in the nearshore zone in **1986**, with most of the water being above or within the **pycnocline** layer. However, there were some differences between the whale feeding stations and the control stations near the **Kongakut** Delta. Subsurface waters were generally **cooler** and more saline with sharper **pycnoclines** at whale feeding stations than at corresponding control stations (see 'Water Masses', p. 103-114). The **whale** feeding stations were **closer** to shore than associated control stations.

Only one station was located in this zone in **1985**, while eight nearshore stations along broad-scale transects were sampled in 1986. Consequently, between year comparisons should be treated with some caution. For 1986, the nearshore data used below **all** come from the four broad-scale transects. Other stations near feeding whales, and their respective controls, are discussed later.

The **total** biomass of **zooplankton** per cubic meter of water was higher in the nearshore zone than farther offshore. In 1986, this was true for each specific layer (above **pycnocline**, **pycnocline**, Arctic Water below **pycnocline**) and for the water column as a whole (Fig. 76). In 1985, when there was only one nearshore station, the same trend was true for 'Above **Pycnocline**' and the water column as a whole.

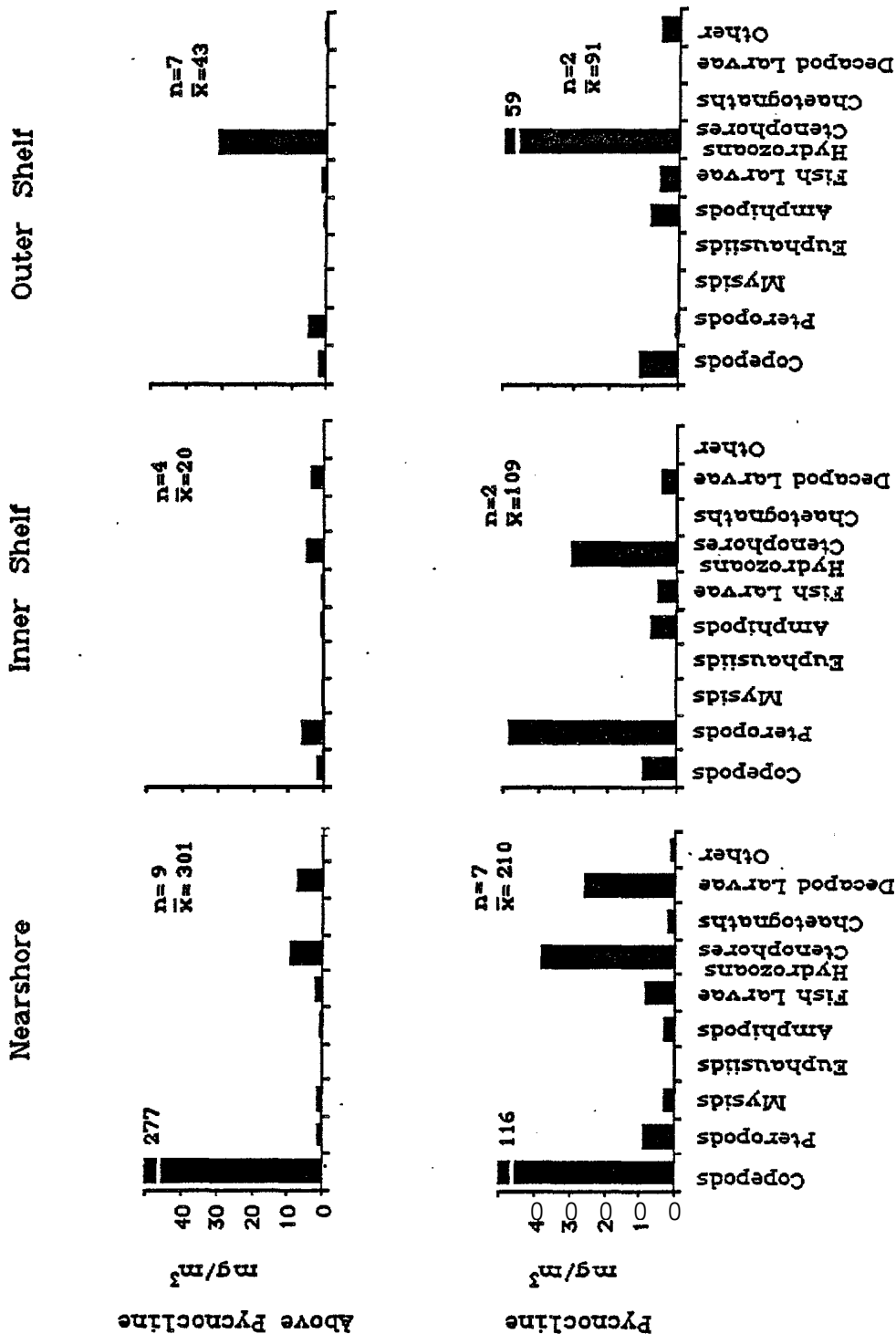
In the water column as a whole, there were three major groups of **zooplankton** in 1986: **copepods**, **decapod larvae** and the **hydrozoan** plus **ctenophore** group (Fig. 76). Major groups were defined as those contributing greater than 10 mg/m<sup>3</sup> to total biomass. In 1985, **copepods** and **hydrozoans** plus **ctenophores** were also major contributors along with mysids and euphausiids (Fig. 78). The species composition of the major and minor groups varied little between the two years (Fig. 77). In the case of copepods, the dominant group in both years, three species were common in both years: **Limnocalanus macrurus**, **Calanus hyperboreus**, and **Calanus glacialis**. In 1985, **Derjuginia tolli** was also a major contributor to the copepod biomass at the one nearshore station, while in 1986 it was not found in nearshore samples. **Limnocalanus macrurus** was the dominant copepod in the nearshore area in both 1985 and 1986. The average biomass in the water column in 1986 was lower than the biomass in the single 1985 sample (296 vs. 487 mg/m<sup>3</sup>). However, some individual samples from 1986 had higher biomasses (e.g. Sta. T4-1 and T2-2, 1036 and 777 mg/m<sup>3</sup>).

Group composition varied substantially with depth in both years of the study. Samples from surface waters above the **pycnocline** contained fewer **zooplankton** groups than samples from below and within the **pycnocline**. This was true in both years (Fig. 76, 78). Copepods were the only major contributors to **zooplankton** biomass in surface waters in either year, while several groups were major contributors in deeper nearshore water: in 1985, **mysids**, **euphausiids**, and **hydrozoans** plus **ctenophores**; in 1986, **decapod larvae** and **hydrozoans** plus **ctenophores** (Fig. 76, 78).

**Pycnoclines** were generally not as distinct in 1986 as in 1985, and in a number of cases they formed layers that extended from just below the surface, to the bottom, rather than discrete bands (see 'Water Masses' section). In 1986, samples were collected in the Arctic Water below the **pycnocline** layer at only two of the eight nearshore stations. In both cases, copepods were by far the major contributor to total **zooplankton** biomass in the Arctic Water, with only a minor contribution from **hydrozoans** and **ctenophores** (Fig. 76).

In both 1985 and 1986, the highest biomasses in nearshore waters occurred at depth, and **copepods** were by far the dominant component (Fig. 76, 78). The total **zooplankton** biomass at depth in nearshore waters was higher in 1986 (average of 8 stations) than for the single 1985 sample (648 vs. 463 mg/m<sup>3</sup>), and several samples from individual 1986 stations had much higher biomasses (e.g. Sta. T4-2 and T2-2, 2214 and 2149 mg/m<sup>3</sup>; Appendix 2).

In summary, copepods were the dominant **zooplankters** throughout the nearshore zone in both years. These results were consistent with previous findings in and near the study area. Most studies of arctic **zooplankton** have shown copepods to be the dominant group in terms of number (Johnson 1956; Grainger 1965; Hopkins 1969; Grainger and Grohe 1975; Homer 1979, 1981; Bradstreet and Fissel 1986) and biomass (Hopkins 1969; Sekerak et al. 1976a,





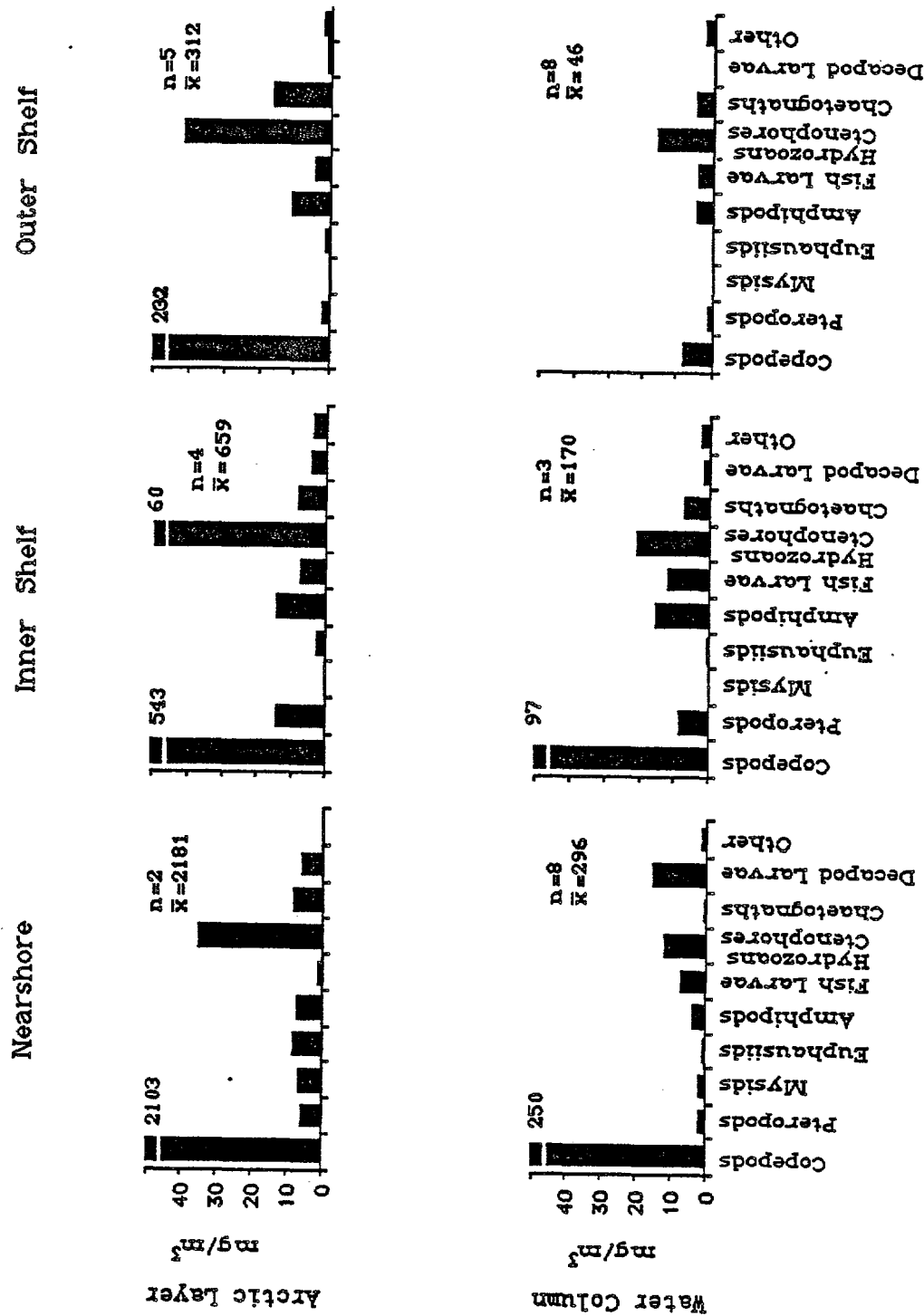


FIGURE 76. Biomass ( $\text{mg}/\text{m}^3$ ) of major zooplankton groups vs. zone and depth, Eastern Alaskan Beaufort Sea, September 1986. For each situation,  $n$  is the number of zooplankton tows considered;  $\bar{x}$  is the mean total biomass for all groups. Based on 1986 Transects T1-T4. Horizontal tows through Bering Sea Water, which occurred over the Outer Shelf on Transects T1-T3, are excluded (see Fig. 79).

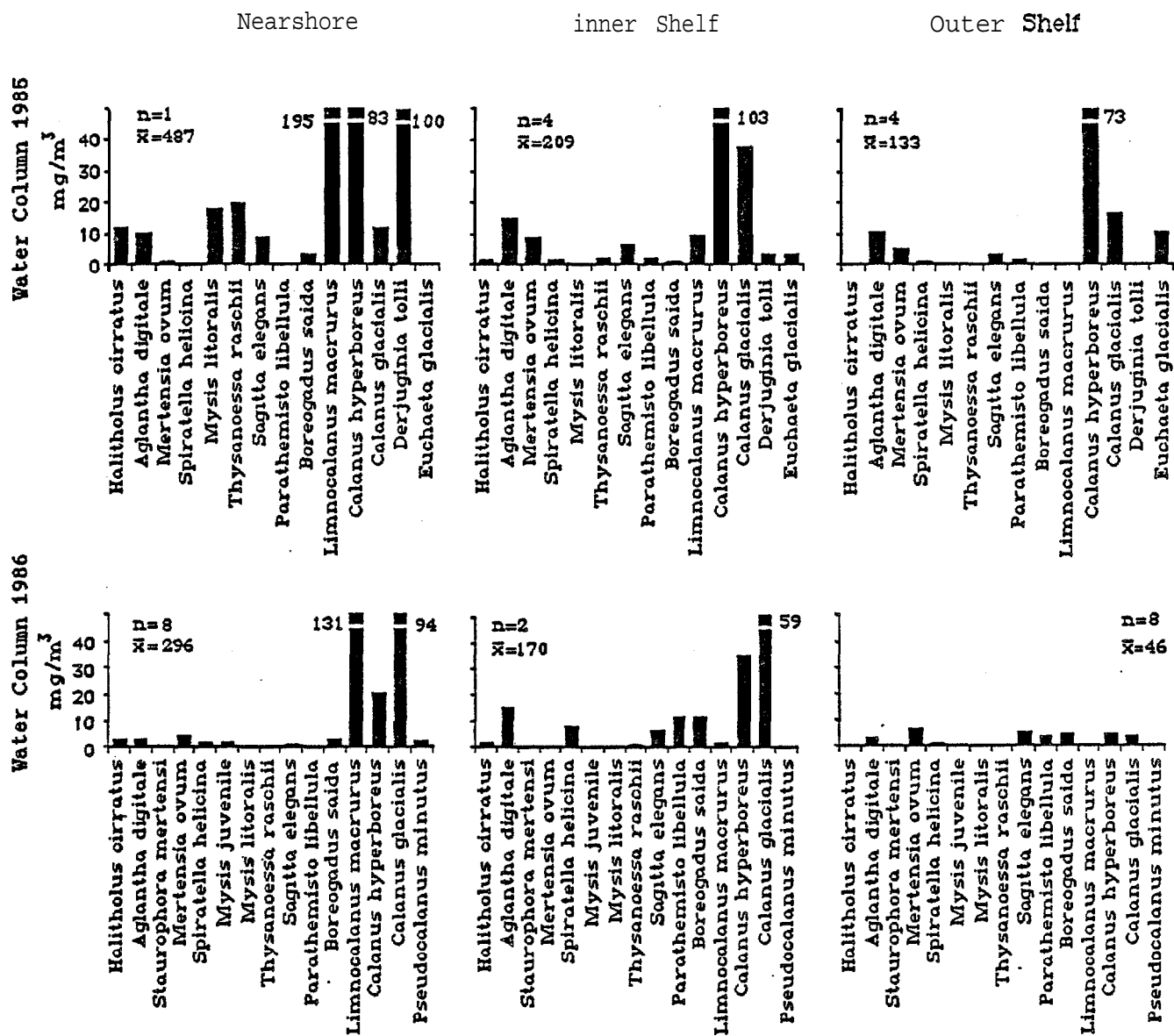


FIGURE 77. Biomass ( $\text{mg}/\text{m}^3$ ) of major zooplankton species in the water column as a whole, Eastern Alaskan Beaufort Sea, September 1985-86. For each situation, n is the number of zooplankton tows considered;  $\bar{X}$  is the mean total biomass for all groups. Based on oblique tows along 1985 Transects 1 and 2, and 1986 Transects T1-T4.

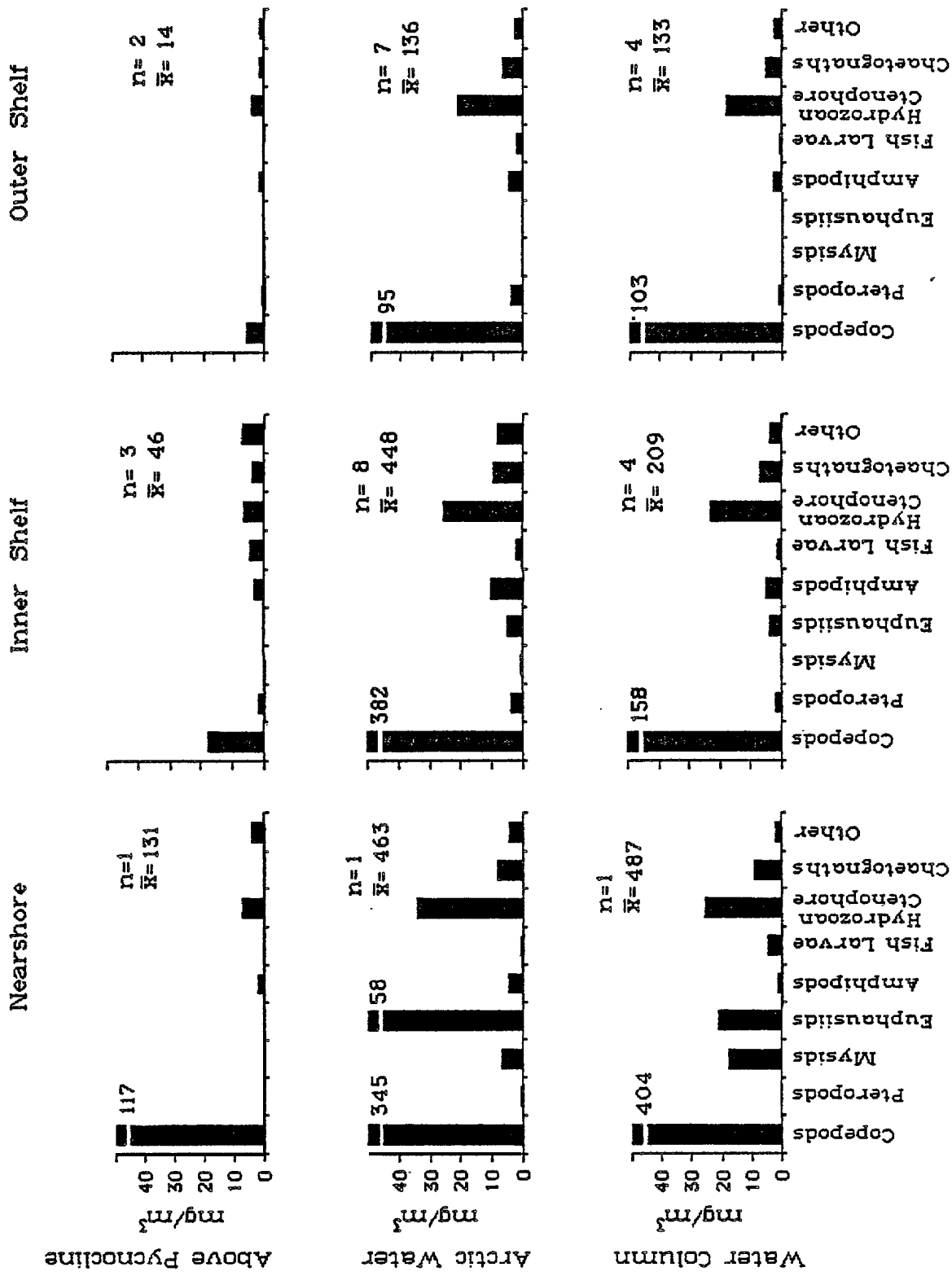


FIGURE 78. Biomass ( $\text{mg}/\text{m}^3$ ) of major zooplankton groups vs. zone and depth, Eastern Alaskan Beaufort Sea, September 1985. For each situation,  $n$  is the number of zooplankton tows considered;  $\bar{x}$  is the mean total biomass for all groups. Based on 1985 Transects 1 and 2.

1979; Griffiths and Buchanan 1982; Bradstreet and Fissel 1986; Bradstreet et al. 1987). However, **hydrozoans**, **chaetognaths** and **ctenophores** have occasionally been found to be dominant at specific stations or depths. For example, Griffiths and Buchanan (1982) found hydrozoans and **ctenophores** to **dominate** at a number of stations off the Mackenzie River delta in 1980-81.

The main **copepod** species found in nearshore waters in both years of the study, **Limnocalanus macrurus**, has typically been reported from nearshore brackish water in the arctic. **Derjuginia tolli** was a dominant **copepod** at the one nearshore station in 1985 but was absent in 1986. This may be either a reflection of yearly variation in abundance or an artifact of the small 1985 sample size.

In 1985, mysids (**Mysis litoralis**) and euphausiids (**Thysanoessa raschii**) were major contributors to total biomass in the nearshore zone. These were present in 1986, but were not major contributors to total biomass along the four broad-scale transects. However, mysids were important at some nearshore locations where bowheads fed in 1986 (see 'Whale Feeding' subsection, p. 187-199). One whale taken off Kaktovik in 1983 had eaten almost entirely mysids (Lowry et al. 1987).

Inner Shelf Waters. --Four 1985 stations (depth range 25 to 45 m) and three 1986 stations (depth range 41 to 47 m) were sampled in this zone (Table 12). At these stations, the **surface** layer was thicker and warmer in 1986 than in 1985 (10 m vs. 5 m; 0 to 2.5°C vs. <1.0°C). In both years waters below the **pycnocline** were **cold** and **saline** (-1.0°C; >30 psu).

In the **inner shelf** zone, the total biomass of **zooplankton** per cubic meter was, on average, less than that closer to shore in the nearshore zone, but more than that farther offshore over the outer shelf. This was true for the **water** column as a whole in both years, and for most specific layers in one or both years (Fig. 76, 78).

In the water column as a whole, the total **zooplankton** biomass during 1986 was dominated by four groups: **copepods**, **hydrozoans** plus **ctenophores**, **amphipods**, and fish larvae (Fig. 76). In 1985, the major groups were **copepods** and **hydrozoans** plus **ctenophores** (Fig. 78). Two species, **Calanus hyperboreus** and **Calanus glacialis**, contributed most of the **copepod** biomass in both years. Most other major groups were represented by low **biomasses** of a single species: hydrozoans by **Aglantha digitale**, amphipods by **Parathemisto libellula**, and fish larvae by **Boreogadus saida**. Average total biomass in the water column as a **whole** was similar in both years (209 vs. 170 mg/m<sup>3</sup> in 1985 and 1986, respectively).

Total zooplankton biomass above the **pycnocline** was low in both 1985 and 1986 (46 and 20 mg/m<sup>3</sup>, respectively). In 1986, no group contributed more than 10 mg/m<sup>3</sup>, and only three groups--pteropods, **decapod** larvae, and hydrozoans plus **ctenophores**--accounted for more than 5 mg/m<sup>3</sup>. In 1985, only copepods were major contributors to **total** biomass in this zone (Fig. 76, 78).

Within the **pycnocline** layer, **pteropods**, hydrozoans plus **ctenophores**, and (barely) **copepods** were major contributors to **zooplankton** biomass during 1986 (Fig. 76). Below the **pycnocline** in the Arctic Water, three groups were major

contributors in both years: copepods, hydrozoans plus ctenophores, and amphipods (Fig. 76, 78). Average total biomass was similar for both years (448 and 659 mg/m<sup>3</sup> in 1985 and 1986, respectively).

Calanus glacialis and C. hyperboreus were the major species over the inner shelf in both years. Limnocalanus macrurus, the dominant copepod in nearshore waters, was present over the inner shelf but was not a major contributor to the biomass in either year. Mysids and euphausiids were not abundant in terms of biomass in inner shelf waters in either 1985 or 1986. However, if these two groups were most abundant at or near the bottom, their abundances may have been underestimated since most horizontal samples were collected well above the bottom.

Outer Shelf Waters.--The four 1985 stations in this zone were in water depths of 56 to 185 m and were characterized by a relatively thick (5 to 7 m) surface layer of water with Mackenzie Bay T/S patterns ( $T = 1.5$  to  $2.5^{\circ}\text{C}$ ;  $S = 23$  to  $26$  psu). Below this layer there was cold, saline Arctic Water. The seven 1986 stations in this zone (depths 53 to 205 m) showed less influence of Mackenzie Bay water than in 1985; in 1986 Mackenzie Bay water was limited to the eastern half of the study area, i.e. the outer portions of Transects T3 and T4. The western outer shelf, i.e. the outer portions of Transects T1 and T2, was covered by colder water. In 1986 two distinct water masses were evident at depth along the outer shelf, Arctic Water and Bering Sea Water (see 'Water Masses' section, p. 84-102).

Total zooplankton biomass in the outer shelf zone was, on average, less than that in nearshore and inner shelf waters (Fig. 76). This was true for the water column as a whole in both years, and for all specific layers aside from the uniformly impoverished surface layer in 1986. The 'water column as a whole' estimates for 1986 are averages for the top 50 m. The 'water column as a whole' estimates for 1985 are roughly comparable, but 2 of the 4 samples extended down to 80 and 100 m. In the water column as a whole, average total zooplankton biomass was higher in 1985 than in 1986 (133 vs. 46 mg/m<sup>3</sup>).

In the water column as a whole, only hydrozoans plus ctenophores were major contributors to total zooplankton biomass in 1986, and even they contributed only 16 mg/m<sup>3</sup> (Fig. 76). In 1985, copepods formed the dominant group, followed by hydrozoans plus ctenophores (Fig. 78). Most major groups were represented by one or two species in each year: hydrozoans by Aglantha digitale, ctenophores by Mertensia ovum, chaetognaths by Sagitta elegans, copepods by Calanus hyperboreus and C. glacialis (Fig. 77). An additional copepod, Euchaeta glacialis, was a major contributor only in 1985.

In surface waters over the outer shelf, total zooplankton biomass was very low in both years (14 and 43 mg/m<sup>3</sup>, respectively). In 1985 two groups, copepods and hydrozoans plus ctenophores, contributed most of this low total biomass. In 1986, only the hydrozoan plus ctenophore group was a major contributor (Fig. 76, 78). Similarly within the 1986 pycnocline layer, the hydrozoan plus ctenophore group was the major contributor to total biomass, with some copepods, amphipods, and fish larvae. Total biomass in this layer was low, but twice that in surface waters (91 vs. 43 mg/m<sup>3</sup>; Fig. 76).

Below the **pycnocline** in Arctic Water, the dominant zooplankton groups were **copepods**, hydrozoans plus ctenophores, and **chaetognaths** in both 1985 and 1986 (Fig. 76, 78). In both years total biomasses were an order of magnitude higher in this layer than in the surface or **pycnocline** layers.

Bering Sea Water was present below the **pycnocline** only in 1986, and only at the north ends of transects T1, T2 and T3 (see 'Water Masses', p. 91-96). **Hydrozoans** plus ctenophores and copepods were the major contributors to total **zooplankton** biomass (Fig. 79). Total biomass averaged 225 mg/m<sup>3</sup>, approximately the same as the average for the Arctic Water mass over the outer **shelf** (312 mg/m<sup>3</sup>, Fig. 76].

In general, **copepods**, hydrozoans plus **ctenophores**, and **chaetognaths** were the major contributors to total biomass over the outer continental **shelf** in both years. However, **copepods** were dominant at all four outer **shelf** stations in 1985, whereas the hydrozoan plus ctenophore group often was dominant there in 1986. In both years, most copepod biomass consisted of *C. hyperboreus* and *C. glacialis*. As in the inner shelf zone, no horizontal tows were taken near the bottom, so any animals concentrated there may be underrepresented.

General Patterns.--Along the two long 1985 transects and the four 1986 transects there was typically a layer of warmer and brackish surface water overlaying colder and more **saline** deeper water. Although salinities of the surface water were similar in the two years (<30 **psu**), this surface layer was generally warmer in 1986 (>1.5 vs. >-0.5°C), with the exception of the off-shore ends of Transects T1 and T2. In 1985, **pycnoclines** were very distinct,

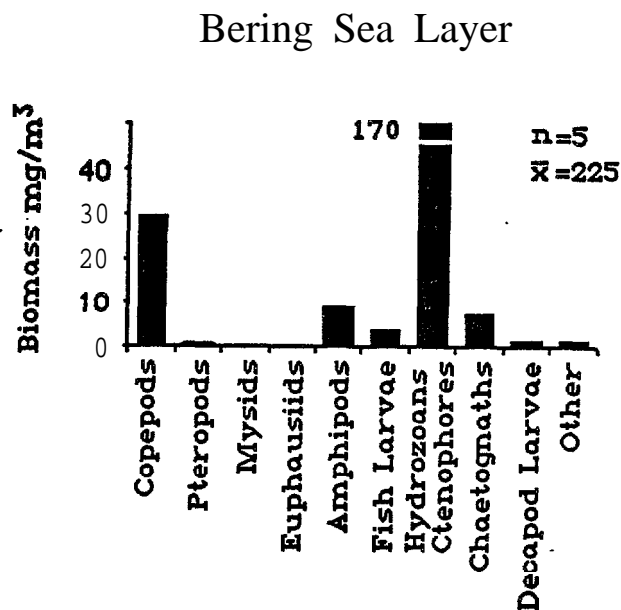


FIGURE 79. Biomass (mg/m<sup>3</sup>) of major zooplankton groups in the Bering Sea Water near the north ends of Transects T1-T3, September 1986. n is the number of zooplankton tows considered; x̄ is the mean total biomass for all groups.

whereas in 1986 they occasionally formed thicker layers that, at some nearshore stations, went from 2-3 m depth to the bottom. In 1985, water below the pycnocline was typically Arctic Water along the entire length of the two transects. In 1986, Arctic Water was found below the pycnocline in the nearshore and inner shelf zones, while in the outer shelf region Bering Sea Water was also present along Transects T1, T2 and T3 but not Transect T4.

Zooplankton biomass in surface waters was almost always low along all transects during both years of study. The one exception was at nearshore stations along Transect T4 in 1986. The low biomass near the surface was mainly attributable to a scarcity of copepods (Fig. 76 and 78; Appendix 2). This may be related to the fact that chlorophyll levels in the surface waters were low in both years (see Fig. 101-105 on p. 229-233; also Griffiths et al. 1986, p. 138-142).

Within the 1986 pycnocline layer, mean biomass was higher than that in the surface layer at inner and outer shelf stations, but not at nearshore stations (Fig. 76). Copepods were the dominant zooplankters in this layer only in the nearshore zone; at inner and outer shelf locations the hydrozoan plus ctenophore group and pteropods were the major contributors to total biomass. Below the pycnocline, biomass was much higher than that close to the surface, and tended to decrease with increasing distance from shore. Below the pycnocline copepods dominated the total biomass in both years.

There were only minor differences in the species composition of the copepod community between years (Fig. 77). In nearshore waters, copepods were dominated by four species in 1985--Limnocalanus macrurus, Derjuginia tolli, Calanus hyperboreus, C. glacialis--and by three species in 1986--L. macrurus, C. hyperboreus, C. glacialis. In both years, L. macrurus was the dominant copepod in the nearshore zone. In the inner and outer shelf zones, the dominant copepods in both years were C. hyperboreus and C. glacialis.

#### Zooplankton Across the Alaskan Beaufort Sea, October 1986

Vertical and oblique tows were collected along five onshore-offshore transects between Pt. Barrow and Demarcation Bay on 4-17 October 1986 during the 'Polar Star' cruise. Two of these transects (C and D) were located near the western and eastern boundaries of the official study area; the others were farther west (Fig. 72 on p. 143). Along the western transects, A+W and B, samples were collected over three depth ranges (mid-shelf, water depths 41-64 m; continental slope, 267-278 m; deep water, 1434-2070 m). Along the eastern transects C and D, samples were collected over two depth ranges (mid-shelf, 55 m; deep water, 1635-1781 m). Generally, the top 50 m of the water column was sampled. The biomasses for the major zooplankton groups are shown in Figure 80 and Appendix 1; the species composition for samples from transects C and D is shown in Figure 81 and Appendix 1.

The major feature of the water masses across the Alaskan Beaufort Sea in October 1986 was the presence of an extensive band of warm saline Bering Sea Water. This water mass extended from Pt. Barrow to Demarcation Bay and typically occurred between depths of 20 and 80 m over the continental shelf break. Temperatures of the Bering Water were generally warmer in the western (4 to 5°C) than the eastern (3 to 3.5°C) portion of the region. Surface waters

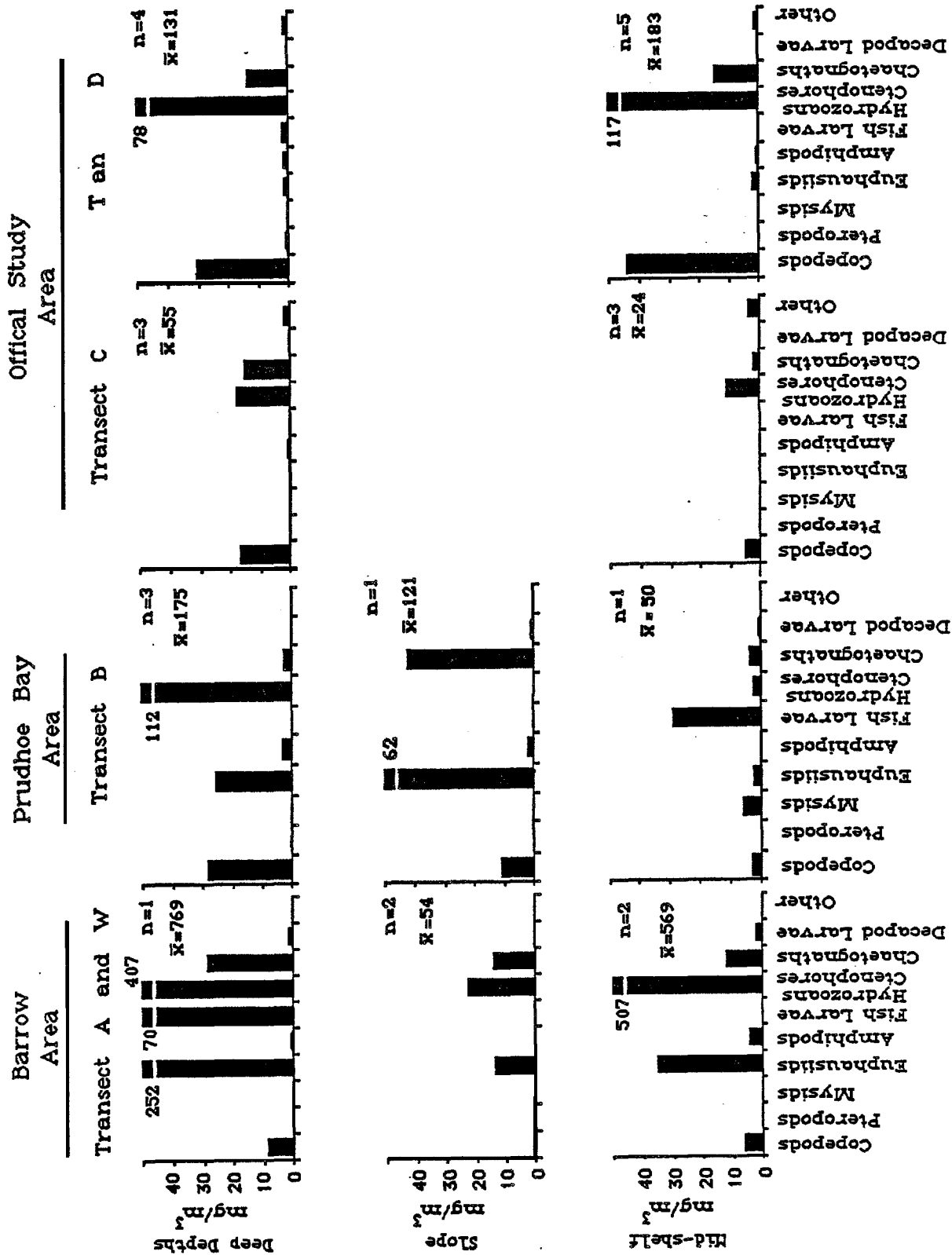


FIGURE 80. Biomass ( $\text{mg}/\text{m}^3$ ) of major zooplankton groups collected in vertical and oblique tows along five transects between Pt. Barrow and Demarcation Bay, October 1986. For each situation,  $n$  is the number of zooplankton tows considered;  $\bar{x}$  is the mean total biomass for all groups in those tows.



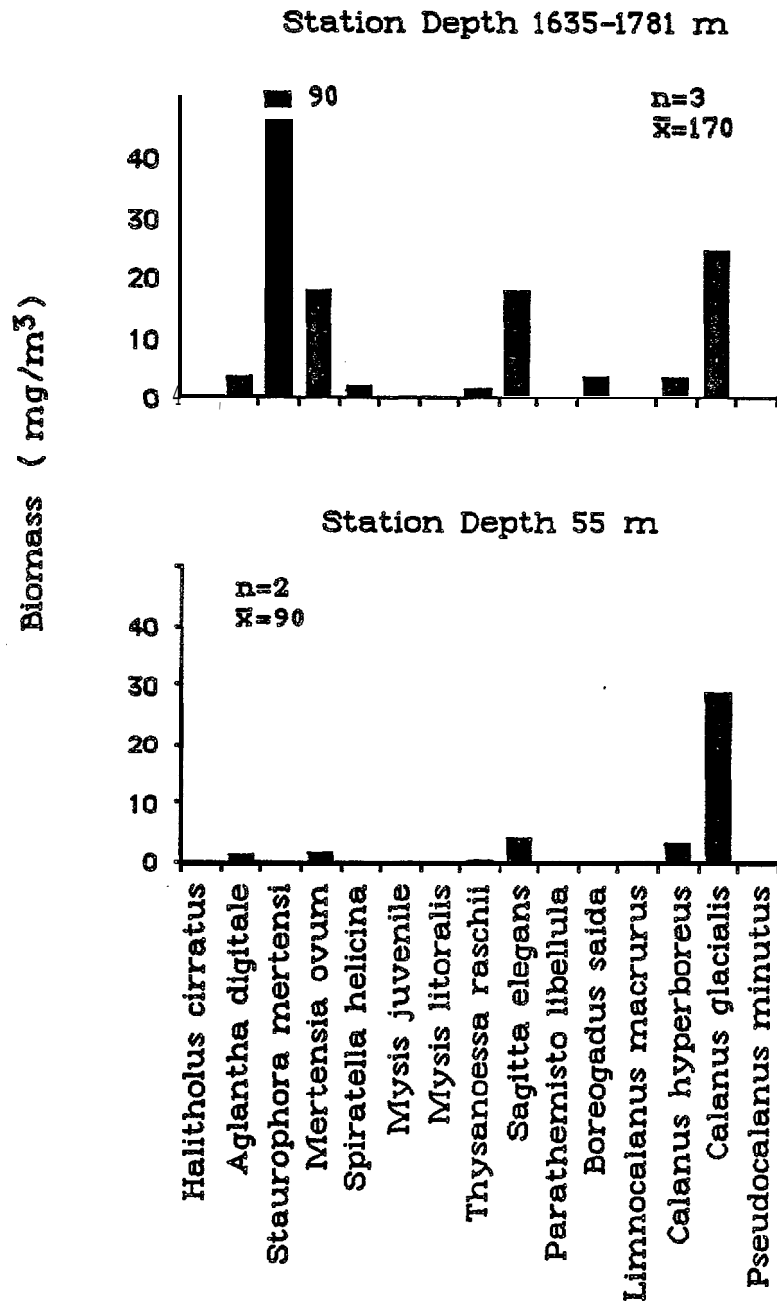


FIGURE 81. Biomass ( $\text{mg}/\text{m}^3$ ) of major zooplankton species collected over mid- and deep water depths along 'Transects C and D, October 1986. For each situation  $n$  is the number of zooplankton tows considered;  $\bar{x}$  is the mean total biomass for all groups in those tows.

(0 to 20 m depth) were cool ( $<-1^{\circ}\text{C}$ ) over the entire region at this time due to extensive ice cover. Most oblique and vertical tows during the cruise were through a combination of the cool surface layer and the Bering Water.

West of Official Study Area.--The major groups that contributed significantly to total zooplankton biomass varied across the coast. Along the westernmost transects (W+A), hydrozoans plus ctenophores dominated over all three depth ranges (mid-shelf, 89%; slope, 46%; deep water, 53% of the total biomass; Fig. 80). Other major groups common to the three depth ranges along Transects W+A included euphausiids (6, 22 and 33%, respectively) and chaetognaths (3, 28 and 4%, respectively). Fish larvae were also major contributors (9% of total biomass) but only at the station over deep water. Noticeable for their scarcity were copepods, which represented only 1, 2 and 1% of the total biomass in samples from mid-shelf, slope and deep stations, respectively (Fig. 80). The high biomass of euphausiids in the Pt. Barrow region was of particular interest since euphausiids dominated the stomach contents of two bowhead whales taken there in autumn (Lowry and Frost 1984).

Over mid-shelf depths (64 m) along Transect B, off Prudhoe Bay, zooplankton biomass was dominated by fish larvae (58% of total biomass), with minor contributions from several other groups (Fig. 80). At the station over the continental slope (depth 267 m), three groups were major contributors to total zooplankton biomass: euphausiids (51%), chaetognaths (36%) and copepods (10%). Over the deep water station hydrozoans plus ctenophores (64%), copepods (17%) and euphausiids (16%) were the dominant zooplankters (Fig. 80). Overall biomass along this transect was lower than that along the westernmost Transects W+A. Euphausiids were again major contributors to total biomass,

Official Study Area.--Along Transect C, near the western boundary of the official study area, samples over mid-shelf waters (55 m) contained low biomasses (mean  $24\text{ mg/m}^3$ ), mainly hydrozoans plus ctenophores (45%), copepods (25%), and chaetognaths (8%; Fig. 80). Over deep stations the total zooplankton biomass averaged  $59\text{ mg/m}^3$ . Again, the main contributors were hydrozoans plus ctenophores (32%), copepods (25%), and chaetognaths (25%). Euphausiids were only minor contributors (1% and  $<1\%$  at mid-shelf and deep stations, respectively).

Along Transect D off Demarcation Bay, total zooplankton biomass was higher than on Transect C, but lower than on Transects W+A. As on Transect C, the biomass at both mid-shelf and deep stations was dominated by hydrozoans plus ctenophores (64 and 60% at mid-shelf and deep stations, respectively), copepods (24% and 24%), and chaetognaths (11 and 10%; Fig. 80). Euphausiids were only minor contributors (about 1%).

The species composition of zooplankton collected over mid-shelf and deep waters along Transects C and D in October 1986 was similar to that in inner and outer shelf waters during September (Fig. 81). Copepod biomass was dominated by Calanus glacialis and C. hyperboreus with a negligible contribution from Limnocalanus macrurus. Chaetognaths were represented by only one species, Sagitta elegans, in samples from both September and October. The major differences occurred in the hydrozoan plus ctenophore group. The small hydrozoan Aglantha digitale was common in both sampling periods, as was the ctenophore Mertensia ovum. However, the large hydrozoan Staurophora mertensi,

the major contributor to hydrozoan biomass over deeper water in October, was not found in continental shelf waters in September. The absence of zooplankters typically reported as associated with Bering Sea Water (i.e. the copepod Neocalanus cristatus) was surprising considering the unusual extent of this water mass across the Alaskan Beaufort Sea during October 1986.

Considering the Alaskan Beaufort Sea as a whole, zooplankton biomass in the top 50 m during October 1986 was generally greater over deep water stations than over the continental slope or mid-shelf stations, and decreased from west to east. important features of the zooplankton community included (1) the abundance of euphausiids, in terms of biomass, in the western and middle portions of the Alaskan Beaufort Sea and their near absence in the official study area, and (2) the low contribution from copepods across the entire area at this time of year. The decrease in copepod biomass from September to October may have been a result of downward migration into deeper Arctic Water to breed and/or overwinter. For example, Calanus hyperboreus is known to overwinter at considerable depths (150 m) in the central Arctic Ocean and in Jones Sound (Dawson 1978; Head and Harris 1985").

#### Zooplankton in Whale Feeding Areas, September 1986

When boat-based sampling began on 4 September 1986, bowhead whales were already in the southeastern corner of the official study area off the Kongakut Delta and farther east off the Yukon coast (see Fig. 122, 127 in 'Bowheads' section, p. 285, 290). Consequently, fine-scale surveys of zooplankton near concentrations of bowhead whales were conducted immediately upon our arrival in the study area. Between 4 and 7 September we sampled feeding and control stations at five locations where whales were feeding, or had been feeding' within the preceding 24 h. Two of these locations were in Canadian waters west of Herschel Island, and the other three were in the official study area near the Kongakut Delta (Fig. 70, 71). At the two Canadian locations, no bowhead whales were observed from the boat during the actual sampling but several had been seen from the aircraft on the preceding day. In Alaskan waters, numerous whales were either observed from the boat at the start of each sampling session or had been seen from the aircraft earlier that day prior to the arrival of the boat.

Extensive oceanographic measurements were taken at and between the apparent whale feeding and control stations during each session. Thus, a more detailed description of the water masses near areas where whales did and did not concentrate was possible.

West of Herschel Island, 4 Sept. --The first feeding site that we studied was located 5 to 8 km off the Firth River delta, immediately west of Herschel island (Fig. 71 on p. 143). Although no bowhead whales were observed during sampling on 4 September, aerial observers saw about 10 feeding whales -at station 86-1 on 3 September. The CTD profiles at our two stations were different. Although both the feeding station (86-1) and the control station (86-2) had surface layers of warm brackish water, the layer was thicker and the underlying pycnocline more intense at the feeding station (Fig. 82A). At depth, the water was colder and more saline at the control station than at the feeding station; this result differed from all other feeding-control comparisons described later (Fig. 82).

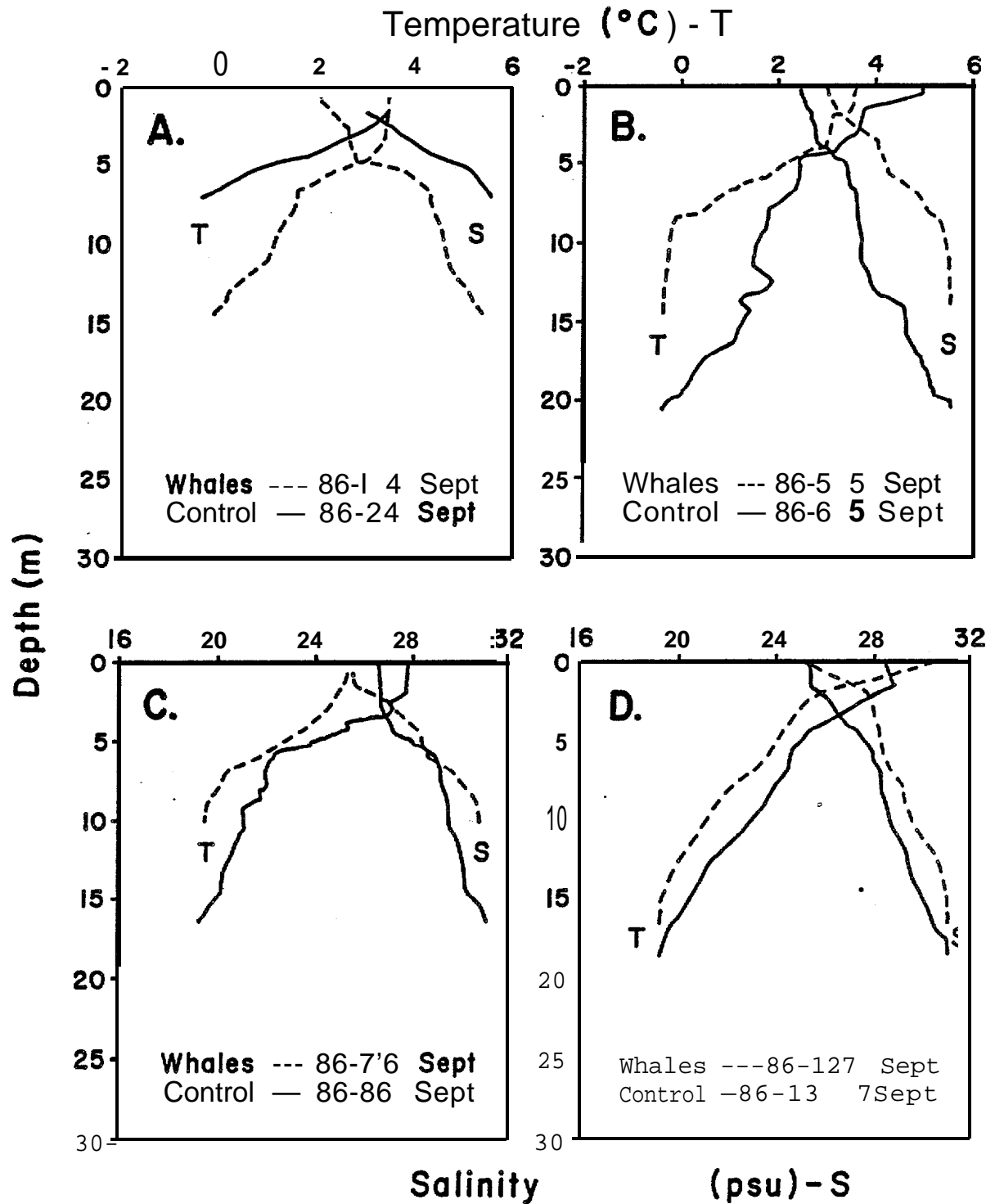


FIGURE 82. Temperature and salinity profiles at four whale feeding stations and corresponding control stations, 4-7 September 1986.

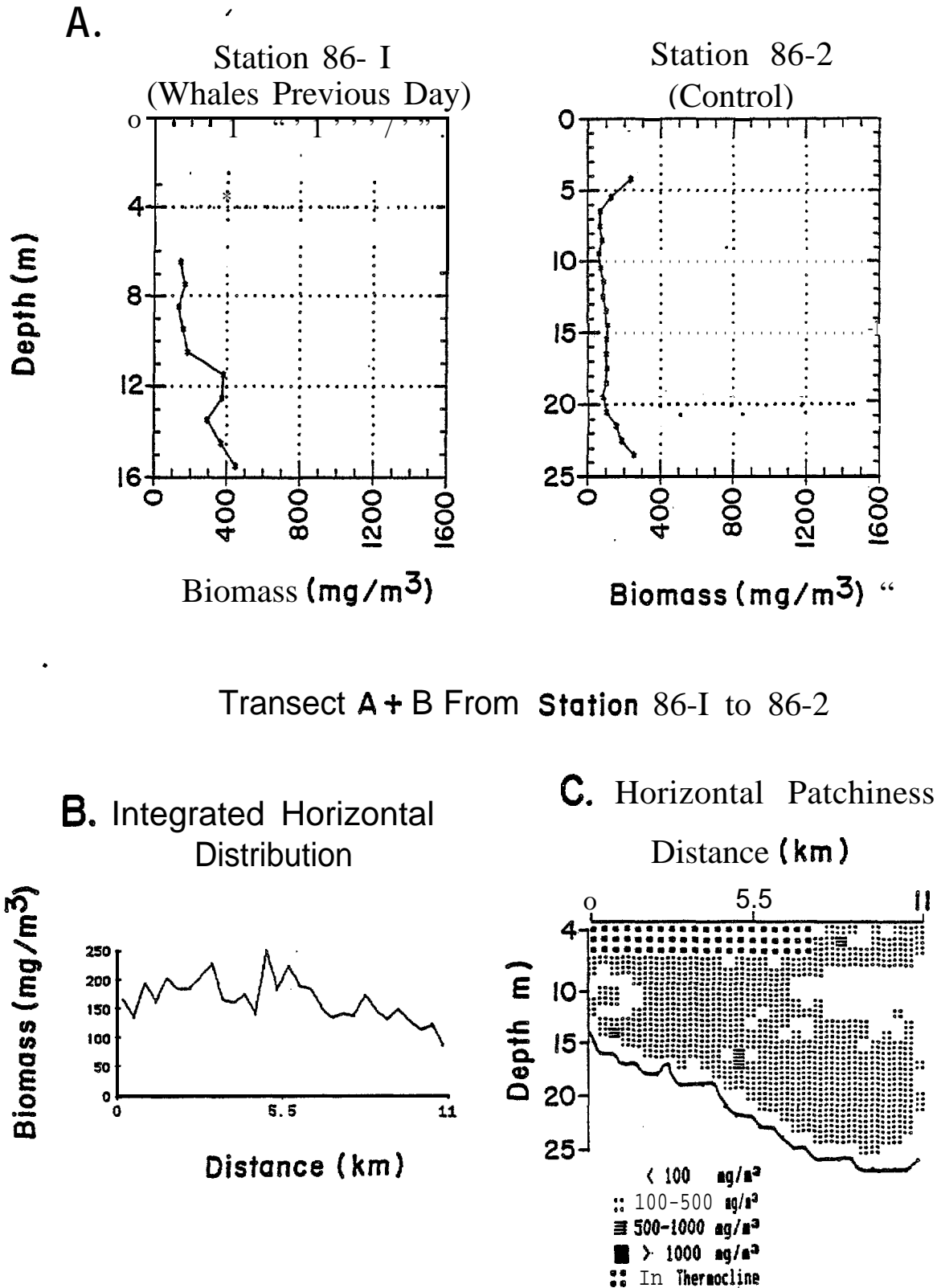
The vertical distributions of estimated zooplankton biomass, based on hydroacoustic data, revealed only thin zooplankton layers near the bottom at both stations (Fig. 83A). Total net biomass in each layer was low (Sta. 86-1: 74 mg/m<sup>3</sup> at 13 m; Sta. 86-2: 213 mg/m<sup>3</sup> at 22 m), as was the average biomass in the water column as a whole at each station (96 and 52 mg/m<sup>3</sup> at Sta. 86-1 and 86-2, respectively; Table 13A). The depth-integrated horizontal distribution of biomass (Fig. 83B) and the absence of dense zooplankton patches (Fig. 83C) suggested that zooplankton levels were low (<300 mg/m<sup>3</sup>) between the two stations. It is possible that water masses and zooplankton in these areas had changed from those present on the previous date, when about 10 bowheads had been present. The unremarkable zooplankton biomass present during sampling may account for the departure of the bowheads before the time of sampling.

At Sta. 86-1, the hydrozoans plus ctenophores group dominated the biomass (38%) while copepods accounted for only 15% (Table 13A). At Sta. 86-2, copepods dominated (78%; Table 13A). Limnocalanus macrurus was the dominant copepod at both stations. The dominance of L. macrurus, especially at Sta. 86-2, was surprising given the cool temperatures and high salinities at this station. Apparently, this nearshore brackish species can tolerate colder and more saline water than previously reported.

Kongakut Delta, 5 Sept. --Numerous bowhead whales were observed from the boat at the feeding station (86-5; Fig. 70 on p. 142) just prior to sampling on 5 September 1986. No bowheads were seen during sampling at the control station (86-6) on that date. The CTD profiles showed that the stations were located in two different water masses. Waters at the nearshore feeding station were colder and more saline than those slightly farther offshore at the control station. The surface layer was also thinner and the pycnocline was more intense at the feeding station (Fig. 82B).

The vertical distribution of estimated biomass at the whale feeding station included a thick zooplankton layer extending from approximately 8 m to the bottom with acoustic biomass 500 to 1000 mg/m<sup>3</sup> (Fig. 84A). In contrast, at the control station there was only a thin layer at 20 m depth with acoustic biomass about 400 mg/m<sup>3</sup>. Net sampling in the distinct layer at the feeding station revealed biomasses of 3023 mg/m<sup>3</sup> (97% copepods) at 10 m depth and 1269 mg/m<sup>3</sup> (95% copepods) at 6 m depth. At the control station, the net biomass within the layer was 92 mg/m<sup>3</sup> (16% copepods; Appendix 2). The average net biomass in the water column as a whole followed a similar pattern (1228 vs. 81 mg/m<sup>3</sup> at the feeding and control stations, respectively; Table 13B). The highest zooplankton biomasses were located close to shore where whales had been observed feeding (Fig. 84B,C). These data suggested that below the pycnocline, zooplankton biomass near the whale feeding station exceeded 1 g/m<sup>3</sup> over a horizontal distance of 2 to 3 km along the onshore-offshore axis.

Two zooplankton groups were major contributors to the total net biomass at the whale feeding station: copepods and hydrozoans plus ctenophores (95 and 3%, respectively; Table 13B). Five copepod species were collected at this station but only one, Limnocalanus macrurus, was a major contributor (95% of total biomass; Table 13B; Appendix 1). At the control station, seven zooplankton groups were major contributors to the much lower total biomass, with hydrozoans plus ctenophores being the single most important group (38%). Copepods were far more abundant at the feeding station than at the control

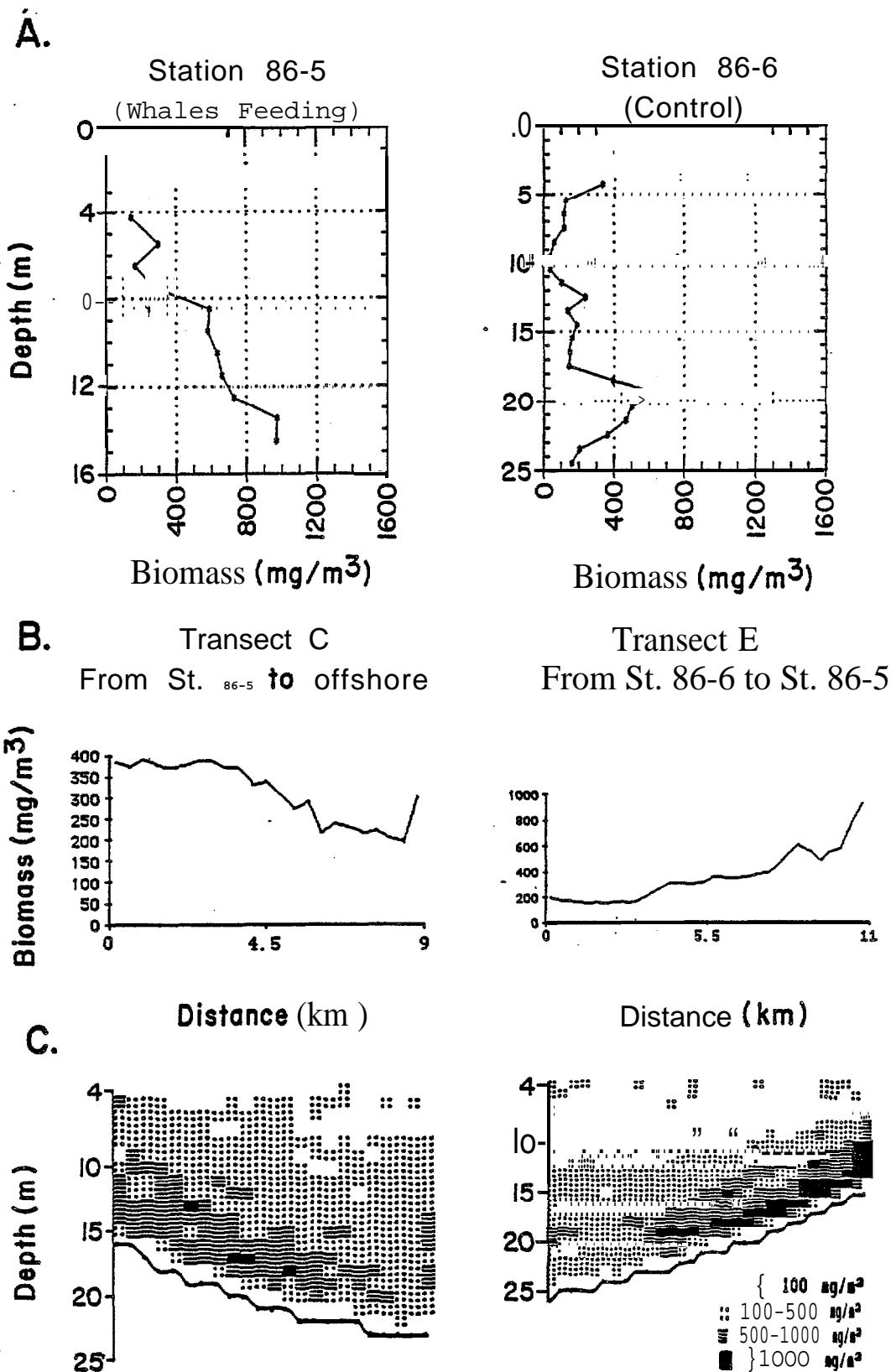


**FIGURE 83.** Hydroacoustic distributions of estimated zooplankton biomass near Herschel Island at whale feeding Station 86-1, control Station 86-2, and along a transect between them (cf. Fig. 71). (A) vertical distribution at stations, (B) depth-integrated horizontal distribution between stations, (C) patchiness between stations. Based on 200 kHz echosounder data, 4 Sept 1986.

**Table 13.** Major zooplankton groups and species collected in oblique tows at apparent whale feeding and corresponding control stations, 4-7 September 1986. Sample depth is the maximum depth of the oblique tow, which was near the bottom (see Table 6 for station depths),

Location	Sample Depth (m)	Zooplankton Biomass mg/m <sup>3</sup>	Taxa Comprising >1% of Biomass	%	Taxa Continued	%
<b>A. 4 Sept 1986, W of Herschel Is land</b>						
Sta. 86-1 (Whales <sup>a</sup> )	16	96.4	Copepods	14.5	Amphipods	13.0
			<u>Limnocalanus macrurus</u>	7.7	Mysids	5.9
			<u>Calanus hyperboreus</u>	2.3	Fish Larvae	2.9
			<u>Calanus glacialis</u>	2.5	Chaetognaths	3.0
			<u>Pseudocalanus minutus</u>	1.4	Decapod larvae	13.9
			Hydrozoans & Ctenophores	38.1	Pteropods	5.2
Sta. 86-2 (Control)	20	51.8	Copepods	78.5	Fish larvae	5.9
			<u>Limnocalanus macrurus</u>	43.1	Hydrozoans & Ctenophores	5.6
			<u>Calanus hyperboreus</u>	17.8	Decapod larvae	4.8
			<u>Calanus glacialis</u>	11.8	Chaetognaths	1.4
			<u>Euchaeta glacialis</u>	2.3	Amphipods	1.2
			<u>M. longa</u>	1.9		
<b>B. 5 Sept 1986, Kongakut Delta</b>						
Sta. 86-5 (Whales)	12	1228.1	Copepods	96.0		
			<u>Limnocalanus macrurus</u>	95.0		
			Hydrozoans & Ctenophores	2.5		
Sta. 86-6 (Control)	22	81.2	Copepods	17.3	Fish larvae	15.7
			<u>Calanus glacialis</u>	10.8	Decapod larvae	7.2
			<u>Limnocalanus macrurus</u>	4.2	Amphipods	4.0
			<u>Calanus hyperboreus</u>	1.5	Chaetognaths	1.3
			Hydrozoans & Ctenophores	38.1	Pteropods	14.0
<b>C. 6 Sept 1986, Kongakut Delta</b>						
Sta. 86-7 (Whales)	8	853.4	Copepods	91.1		
			<u>Limnocalanus macrurus</u>	88.4		
			<u>Pseudocalanus minutus</u>	1.3		
			Mysids	6.3		
Sta. 86-8 (control)	23	40.5	Copepods	31.7	Amphipods	38.0
			<u>Limnocalanus macrurus</u>	18.5	Hydrozoans & Ctenophores	12.3
			<u>Calanus glacialis</u>	4.7	Decapod larvae	4.3
			<u>Euchaeta glacialis</u>	3.5	Chaetognaths	3.3
			<u>Calanus hyperboreus</u>	2.7	Pteropods	2.4
<b>D. 7 Sept 1986, Clarence Lagoon</b>						
Sta. 86-10 (Whales <sup>a</sup> )	12	605.0	Copepods	33.8	Decapod larvae	6.0
			<u>Limnocalanus macrurus</u>	32.0	Mysids	4.6
			Hydrozoans & Ctenophores	41.7	Pteropods	2.9
			Fish larvae	7.5	Amphipoda	1.9
Sta. 86-ii (control)	12	198.5	Copepods	57.4	Hydrozoans & Ctenophores	26.8
			<u>Limnocalanus macrurus</u>	46.7	Fish larvae	3.2
			<u>Calanus glacialis</u>	6.9	Chaetognaths	3.4
			<u>Calanus hyperboreus</u>	2.2	Decapod larvae	3.9
			<u>Pseudocalanus minutus</u>	1.3	Amphipods	1.9
<b>E. 7 Sept 1986, Kongakut Delta</b>						
Sta. 86-12 (Whales)	18	912.4	Copepods	95.3	Fish larvae	1.2
			<u>Limnocalanus macrurus</u>	93.8	Hydrozoans & Ctenophores	1.2
Sta. 86-13 (Control)	21	58.7	Copepods	1.1	Hydrozoans & Ctenophores	16.6
			<u>Limnocalanus macrurus</u>	1.0	Pteropods	9.8
			Fish larvae	33.7	Amphipods	1.2
			Decapod larvae	24.8	Other	12.7

<sup>a</sup> Whales present previous day but not at time of zooplankton sampling.



**FIGURE 84.** Hydroacoustic distributions of estimated zooplankton biomass off the Kongakut Delta at whale feeding Station 86-5, control Station 86-6, and along transects between them (cf. Fig. 70). (A) vertical distribution at stations, (B) depth-integrated horizontal distribution between stations, (C) patchiness between stations. Based on 200 kHz echosounder data, 5 Sept 1986.



station (1179 vs. 14 mg/m<sup>3</sup>), but the total contribution of other groups was virtually identical at the two stations (62 vs. 67 mg/m<sup>3</sup>, respectively),

Kongakut Delta, 6 Sept. --On 6 September, 1986 we again sampled near whales off the Kongakut River delta in the same general area as the sampling on 5 September 1986. Again, numerous bowhead whales were observed from the boat at the feeding station (Sta. 86-7) and none were seen at the control station slightly farther offshore (Sta. 86-8). The temperature-salinity patterns were similar to those the previous day, but the differences between stations were not as large (Fig. 82C).

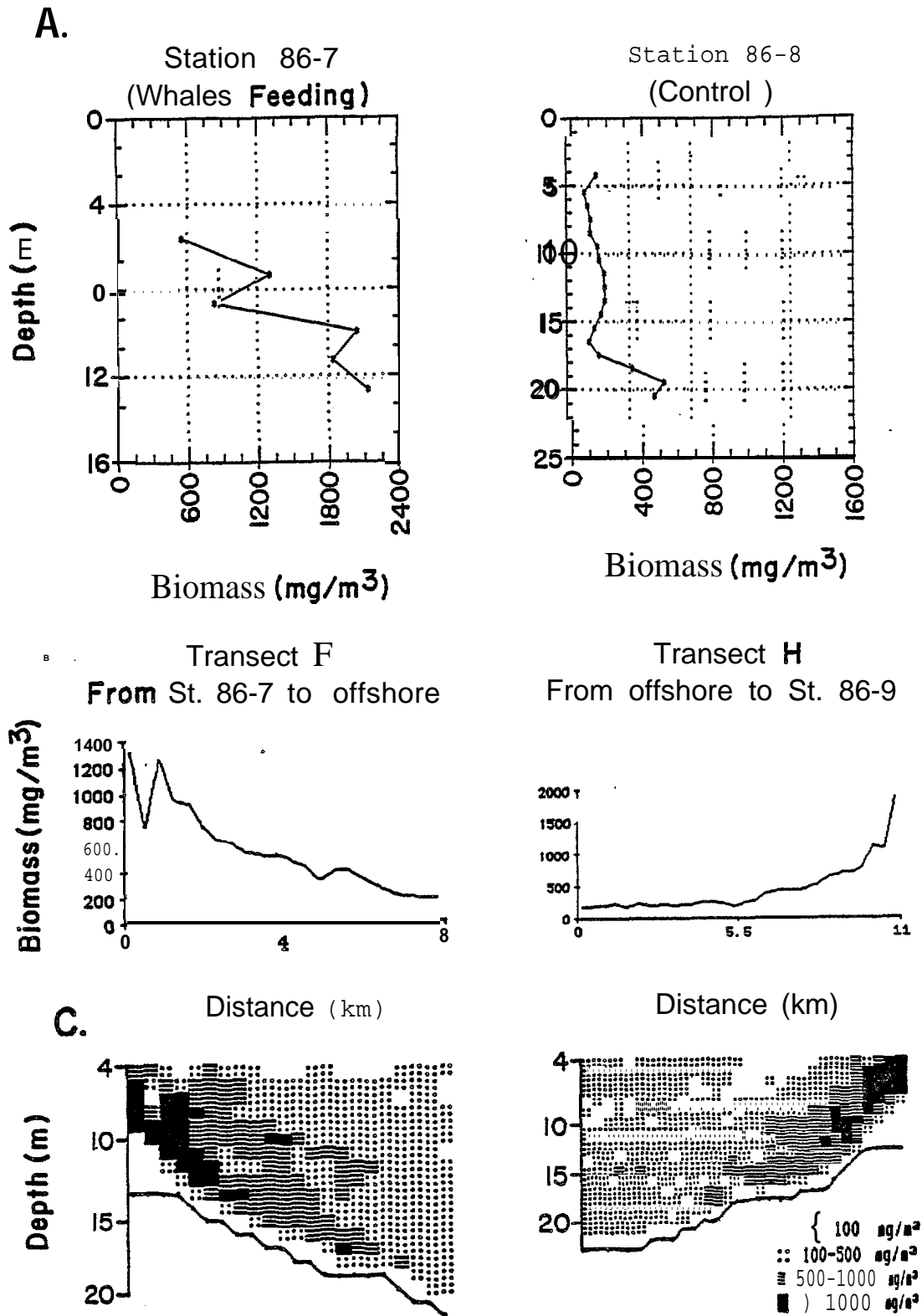
There was again an extensive layer of zooplankton between 4 and 13 m depth at the feeding station (acoustic biomass 400 to 2200 mg/m<sup>3</sup>), and only a thin layer at 20 m depth at the control station (600 mg/m<sup>3</sup>) (Fig. 85A). Net sampling in these distinct layers showed an average biomass of 2069 mg/m<sup>3</sup> (84% copepods) at the feeding station and 1280 mg/m<sup>3</sup> (88% copepods) at the control station (Appendix 2). In the water column as a whole, biomass was about 21 times greater at the feeding than at the control station (853 vs. 41 mg/m<sup>3</sup>; Table 13C), presumably because of the thicker as well as denser zooplankton layers at the feeding station. Hydroacoustic transects showed that biomass below the pycnocline exceeded 1 g/m<sup>3</sup> over a horizontal distance of about 2-3 km from Station 86-7 (Fig. 85B,C).

At the whale feeding station only two groups of zooplankton were major contributors to the total biomass: copepods (91%) and mysids (6%). The dominant copepod species were Limnocalanus macrurus (88% of total biomass) and Pseudocalanus minutus (1%); Mysis litoralis was the only mysid found (Table 13C; Appendix 1). At the control station, amphipods (38%), copepods (32%), and hydrozoans plus ctenophores (12%) contributed most of the biomass.

Again, the major difference between the whale feeding and control stations was the abundance of copepods at the feeding station. The biomasses of all other groups combined were similar at the two stations (76 vs. 28 mg/m<sup>3</sup>, respectively).

Clarence Lagoon, 7 Sept. --This site was located approximately 10 km east of Demarcation Bay along the Yukon coast (Fig. 71). Eight bowhead whales had been observed from the aircraft in this area on 6 September; at this time the waters in the region appeared clear. When sampling began on 7 September no whales were visible from the boat at either the feeding or the control station and only one was seen from the aircraft. A thin (0.5 to 1.0 m) layer of turbid water covered the area where whales had been observed the previous day and where the feeding station (86-10) was positioned. The CTD profiles at the feeding and control stations were virtually identical (see Fig. 56 on p. 109).

Distinct zooplankton layers were present at both stations (Fig. 86A). At the feeding station two layers were apparent: one at 8 m depth (acoustic biomass 1500 mg/m<sup>3</sup>) and the other at 12 m depth (1400 mg/m<sup>3</sup>). At the control station a single relatively thick layer was present from 8 to 12 m depth; acoustic biomass was 400 to 1400 mg/m<sup>3</sup> (Fig. 86A). Net tows within the layers at Sta. 86-10 (whales) showed biomasses of 3847 mg/m<sup>3</sup> (97% copepods) at 8 m depth and 3119 mg/m<sup>3</sup> (94% copepods) at 11 m depth. A tow at 12 m depth in the single layer at Sta. 86-11 (control) showed a biomass of 1149 mg/m<sup>3</sup> (75%



**FIGURE 85.** Hydroacoustic distributions of estimated zooplankton biomass off the Kongakut Delta at whale feeding Station 86-7, control Station 86-8, and along transects between them (cf. Fig. 70). **(A)** vertical distribution at stations, **(B)** depth-integrated horizontal distribution between stations, **(C)** patchiness between stations. Based on 200 kHz echosounder data, 6 Sept 1986.

copepods, 11% hydrozoans and ctenophores, 8% mysids; Appendix 2). In the water column as a whole, the average biomass at the two stations was similar (105 vs. 199 mg/m<sup>3</sup>, respectively; Table 13D). This was probably the result of the thickness of the layer at the control station as compared to the thinner but denser layers at the feeding station (Fig. 86A). A dense layer of zooplankton of varying thickness extended between the two stations (Fig. 86C). Although the biomass at most depths was low at both stations, at certain depths--particularly at the feeding station--there were biomasses in excess of 1 g/m<sup>3</sup>. However, these high density layers were relatively thin, which may have accounted for the departure of the whales from this site before sampling began.

At the whale feeding station, the major contributors to the total zooplankton biomass in the water column as a whole were hydrozoans plus ctenophores (42%) and copepods (34%; Table 13D). The main species were Halitholus cirratus, Aglantha digitale, and Limnocalanus macrurus. At the control station, copepods contributed 57% and hydrozoans plus ctenophores 27%. The main species were Aglantha digitale (25%) and L. macrurus (47%). Excluding copepods, the contribution of all other zooplankton groups was almost identical at feeding and control stations (70 vs. 85 mg/m<sup>3</sup>, respectively).

Kongakut Delta, 7 Sept.--The site off the Kongakut Delta sampled on 7 September 1986 was the farthest offshore of the feeding stations sampled during the study (Fig. 70). The aircraft crew had just finished photographing a group of 12 bowheads as the boat arrived at the whale feeding station (86-12). As was the case during the previous two sampling sessions off the Kongakut Delta, the CTD profiles showed the waters at the feeding station to be slightly colder and more saline than at the control station slightly farther offshore (86-13; Fig. 82D).

There were two layers of zooplankton at St. 86-12, a thin one at about 7 m depth (acoustic biomass 600 mg/m<sup>3</sup>) and a much thicker layer from 12 to 20 m depth (800-1000 mg/m<sup>3</sup>). At the control station, there was a single thin layer at 17 to 19 m depth (acoustic biomass 500 mg/m<sup>3</sup>; Fig. 87A). At the feeding station, three net tows at 6, 13 and 15 m revealed biomasses of 619, 762 and 2137 mg/m<sup>3</sup>, composed of 97%, 84% and 97% copepods, respectively (Appendix 2). In contrast, at control station 86-13, a horizontal net tow at 17 m depth revealed only 105 mg/m<sup>3</sup>, and was composed of hydrozoans plus ctenophores (56%), decapod larvae (27%), fish larvae (6%), and copepods (6%; Appendix 2). In the water column as a whole, the biomass at the feeding station was about 15 times that at the control station (912 vs. 59 mg/m<sup>3</sup>; Table 13E). The hydroacoustic transect showed high estimated biomasses near and inshore of the feeding station and decreasing biomasses seaward of it (Fig. 87B,C). The zooplankton biomasses near the feeding location, particularly at depth, exceeded 1 g/m<sup>3</sup>.

At the feeding station, copepods contributed fully 95% of the total zooplankton biomass in the water column as a whole (Table 13E). Although six copepod species were found, only Limnocalanus macrurus (94% of total biomass) was a significant contributor (Appendix 1). Similarly, at the three specific depths sampled L. macrurus was the dominant contributor to total biomass: 94%, 72% and 92% at 6, 13 and 15 m, respectively. In contrast, the total biomass in the water column at the control station was much lower, and the dominant

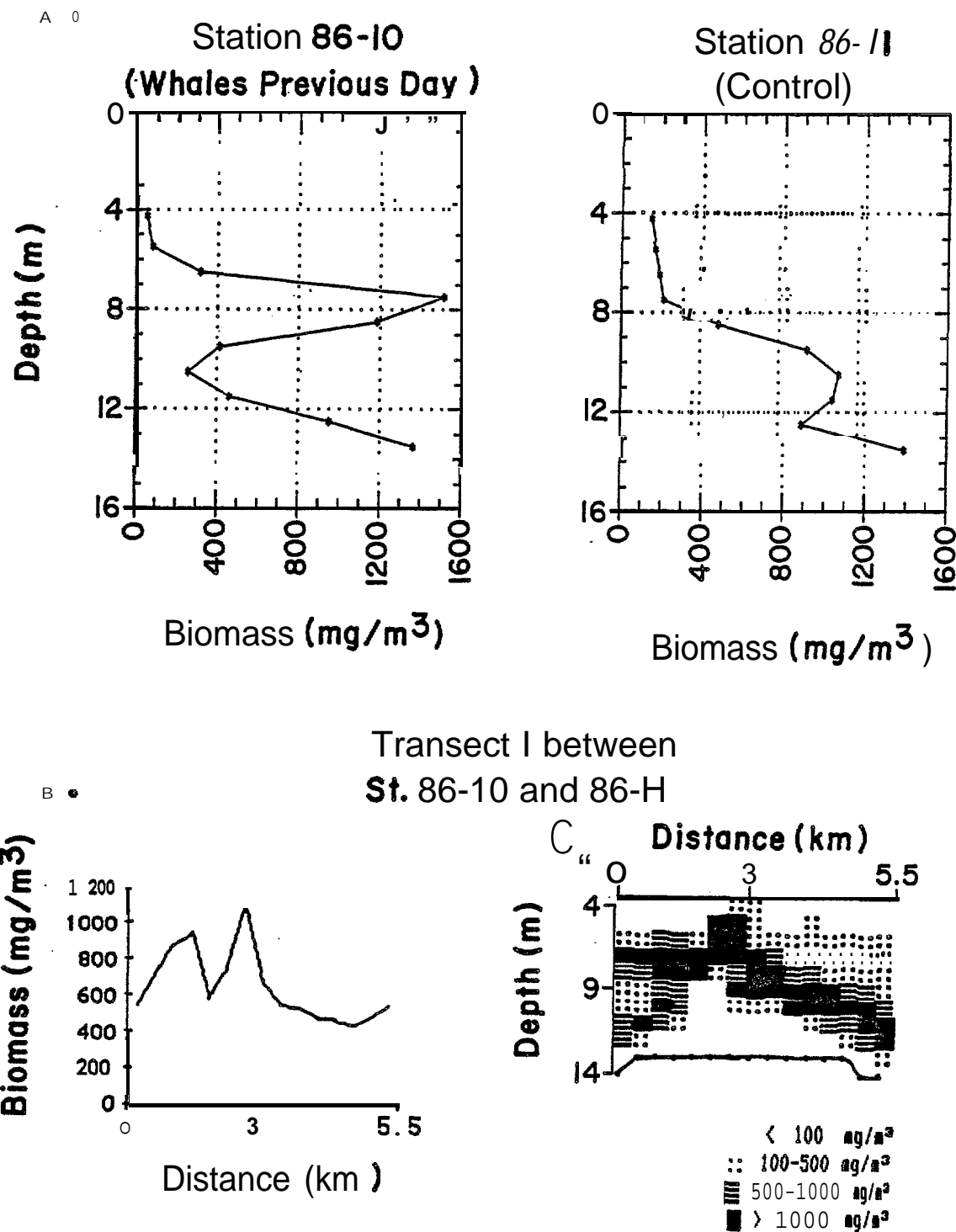


FIGURE 86. **Hydroacoustic** distributions of estimated **zooplankton** biomass off Clarence Lagoon at whale feeding Station 86-10, control Station 86-11, and along transects between them (cf. Fig. 71). (A) vertical distribution at stations, (B) depth-integrated **horizontal** distribution between stations, (C) patchiness between stations. Based on 200 kHz echosounder data, 7 Sept 1986.

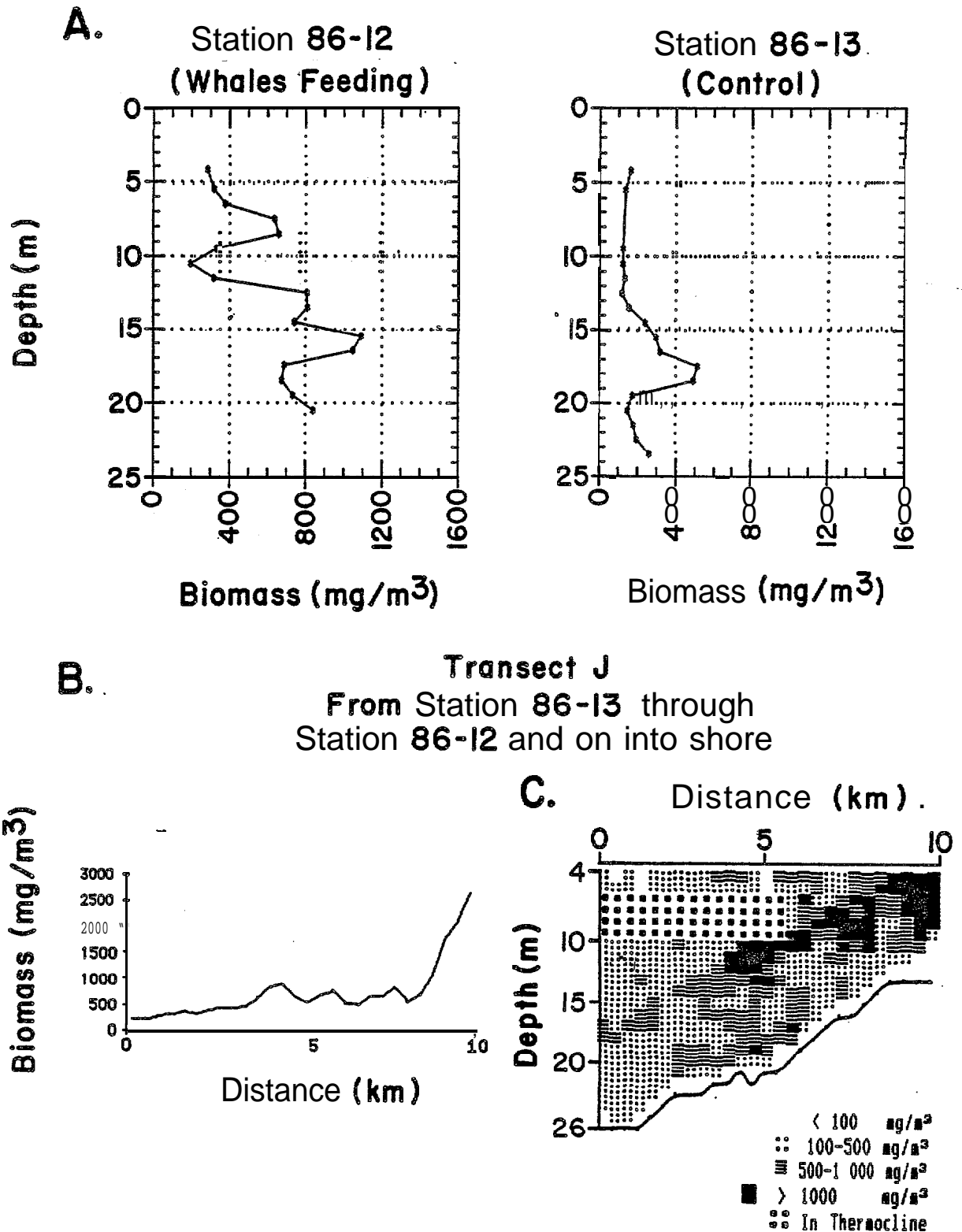


FIGURE 87. Hydroacoustic distributions of estimated zooplankton biomass off the Kongakut Delta at whale feeding Station 86-12, control Station 86-13, and along transects between them (cf. Fig. 70). (A) vertical distribution at stations, (B) depth-integrated horizontal distribution between stations, (C) patchiness between stations. Based on 200 kHz echosounder data, 7 Sept 1986.

groups were "fish larvae (34%), decapod larvae (25%), hydrozoans plus **ctenophores (17%)**, and pteropods (10%). Again the main difference between feeding and control stations was the abundance of **copepods**. Excluding **copepods**, the total biomass of all other groups was similar at feeding and control stations (43 vs. 58  $\text{mg}/\text{m}^3$ , respectively).

**Zooplankton vs. Water Masses at Feeding Locations.**--The net tow data for the five feeding areas were combined according to water masses, as were the data from the corresponding control stations. The group composition in each depth zone is shown in Figure 88; species composition is shown in Figure 89.

Generally, waters were **cooler** and more saline at **whale feeding than** at control stations (see above). At most sites there was a layer of relatively warm brackish surface water (temperature  $>2.0^\circ\text{C}$ ; salinity  $<28$  psu) of varying thickness, overlaying cooler more saline water ( $<0.5^\circ\text{C}$ ;  $>29$  psu). The underlying water appeared to be a mixture of the surface water and Arctic Water (AW).

Total zooplankton **biomasses** in surface waters (above **pycnocline**) at both feeding and control stations were very **low**, averaging 21 and 9  $\text{mg}/\text{m}^3$ , respectively. The slightly higher biomass at the whale feeding stations was attributed to **copepods**, almost exclusively **Limnocalanus macrurus** (Fig. 88, 89). This overall low **zooplankton** biomass in surface waters was consistent with the near absence of observations of surface feeding by bowhead whales in the study area during 1986 (see 'Bowheads' section, p. 333, 361).

Within the **pycnocline** layer, horizontal tow samples were collected both within distinct **zooplankton** layers, as detected with the hydroacoustic system, and at depths where no distinct **layers** were evident. Average **zooplankton biomasses** were high within distinct **layers** at both feeding and control stations (1899 and 845  $\text{mg}/\text{m}^3$ , respectively). Copepods were by far the major contributors at both types of station (93 and 79%, respectively; Fig. 88). However, as illustrated in the previous section, zooplankton layers were generally thicker, usually extending from 6 to 10 m depth to the bottom, at **whale feeding than** at control stations. At depths with no obvious **layers**, average biomasses were **typically** low at both station types, averaging 72  $\text{mg}/\text{m}^3$  at feeding stations and 144  $\text{mg}/\text{m}^3$  at control stations. At both types of **stations**, the lower **biomasses** outside the **layers** were primarily due to a reduction in **copepod** biomass. **Excluding copepods**, the average biomass of all other groups combined was similar within layers (feeding vs. control: 141 vs. 178  $\text{mg}/\text{m}^3$ ) and outside layers (53 vs. 119  $\text{mg}/\text{m}^3$ ).

Arctic Water was evident near the bottom at **only** two control stations, 86-2 and 86-6; it was absent at whale feeding stations. Horizontal tows taken within distinct layers in the Arctic Water at control sites revealed relatively low **biomasses** (mean 187  $\text{mg}/\text{m}^3$ ; Fig. 88), consisting mainly of copepods (59%) and hydrozoans plus ctenophores (23%).

The species composition of **zooplankton** in the water column as a whole was determined for all five feeding and control locations (Table 13, Appendix 1). The copepod **Limnocalanus macrurus** was by far the dominant **zooplankter**, contributing an average of 85% of the **total** biomass in the water column at the five feeding locations (Fig. 89).

Species composition at discrete depths was determined for only one of the five locations, the deepest feeding location. At the whale feeding station (86-12), the copepod L. macrurus was by far the dominant zooplankter at all three depths, representing 94, 72 and 92% of the total biomass at 6, 13 and 15 m, respectively (Fig. 89). Calanus glacialis and C. hyperboreus, two copepod species generally associated with colder Arctic Water (and the dominant copepods in stomachs of most bowheads taken at Kaktovik--Lowry and Frost 1984), were important only at the two deeper depths (13 and 15 m).

The dominance of L. macrurus at all whale feeding stations (and at all three depths at Station 86-12) was somewhat surprising, given the cold water at these stations. This species has been thought to be associated with nearshore brackish water. Apparently it can tolerate a wide range of Temperatures and salinities. L. macrurus was also the dominant zooplankter at whale feeding stations along the Yukon Coast in 1985-86; there too it was most common in cold saline water (Bradstreet and Fissel 1986; Bradstreet et al. 1987).

Biomass Comparisons: Feeding vs. Control Stations, --In the water column as a whole, total biomass was significantly higher at feeding than at control stations when all five sessions were considered (Table 14). Mysids were the only major group for which the difference was significant. However, if only the three locations where feeding bowheads were actually observed during sampling are considered, then both copepod biomass ( $t = 7.01$ ,  $df = 2$ ,  $p = 0.01$ ) and total biomass ( $t = 27.41$ ,  $df = 2$ ,  $p < 0.001$ ) were significantly higher at whale feeding stations. Similarly, the biomass of, Limnocalanus macrurus, the dominant copepod at both feeding and control stations, was significantly higher at the three confirmed whale feeding stations ( $t = 10.3$ ,  $df = 2$ ,  $p < 0.005$ ).

Within distinct zooplankton layers, there were no significant differences between feeding and control stations for any major zooplankton group or for total biomass (Table 14). This was not surprising in view of the low sample size. Also, the previously described hydroacoustic data suggested that one of the main differences between feeding and control stations was in the thickness of zooplankton layers. The layers tended to be thicker at whale feeding than at control stations, particularly at the three locations where bowheads were actually observed during sampling.

#### Major Groups of Zooplankton

Copepods.--Copepod crustaceans were the major components of the zooplankton community in the Eastern Alaskan Beaufort Sea in both 1985 and 1986 and have been found in the stomach contents of most bowhead whales taken at Kaktovik in autumn (Lowry and Frost 1984; Lowry et al. 1987). Five species of copepods were major contributors to the zooplankton community in 1985: Calanus hyperboreus, C. glacialis, Derjuginia tolili, Limnocalanus macrurus and Euchaeta glacialis. Three species were important in 1986: L. macrurus, C. glacialis, and C. hyperboreus. The three species important in both years are discussed below; for an account of the other two species important in 1985, plus Pseudocalanus, see Griffiths et al. (1986, p. 100-101).

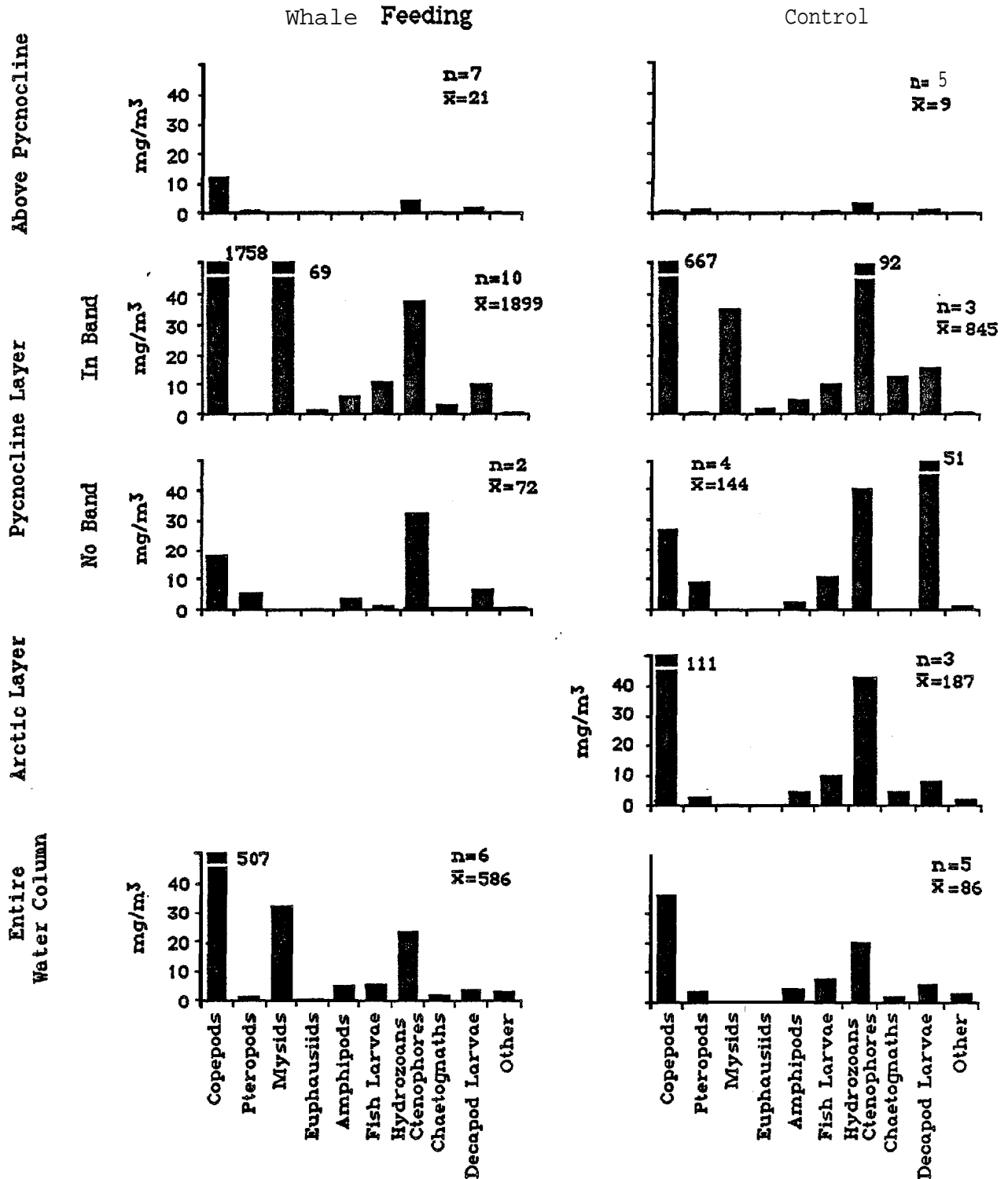


FIGURE 88. Biomass ( $\text{mg}/\text{m}^3$ ) of major zooplankton groups vs. depth at whale feeding and control stations, 4-7 September 1986.



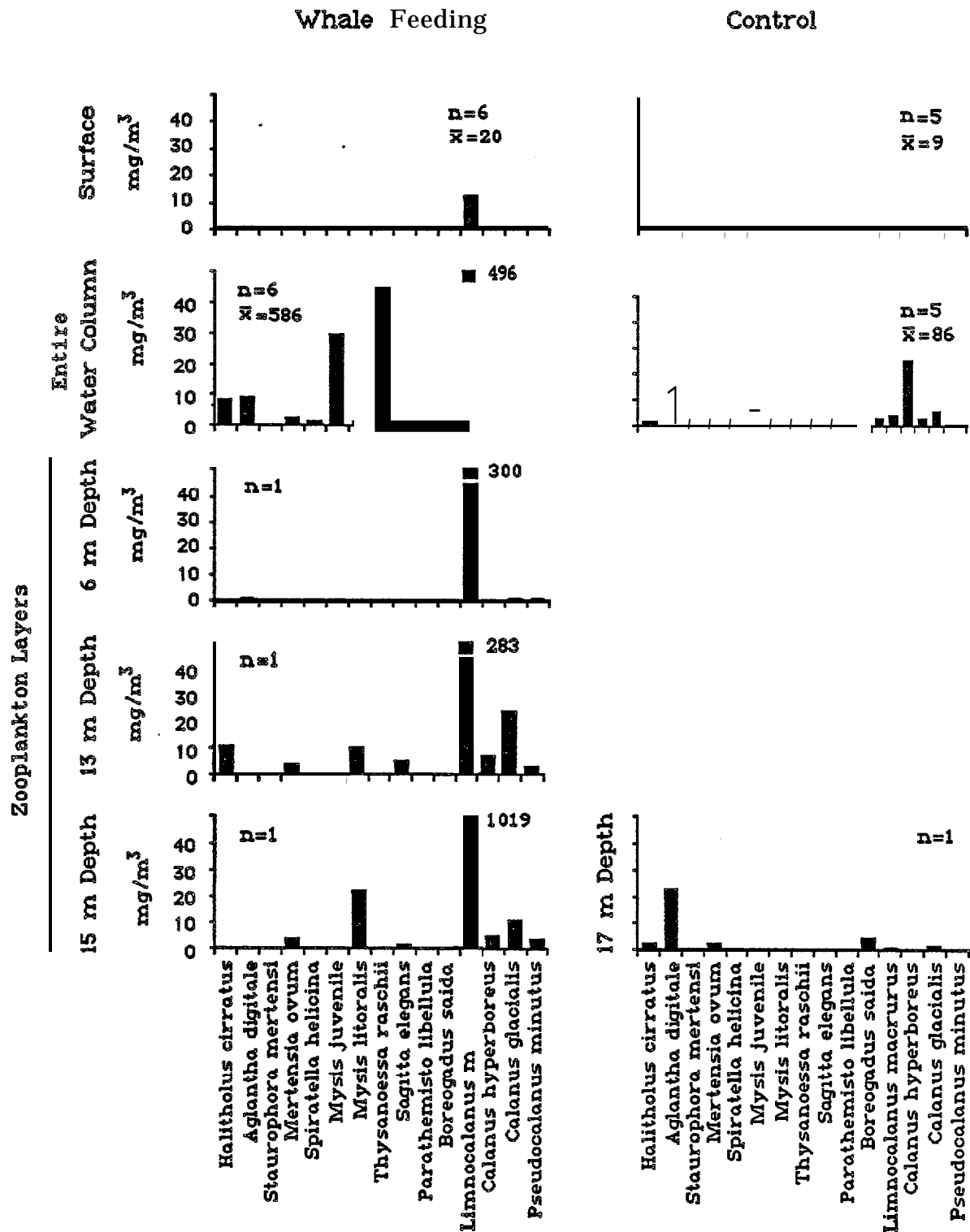


FIGURE 89. Biomass ( $\text{mg}/\text{m}^3$ ) of major zooplankton species collected at whale feeding and control stations, "4-7 September 1986. Zooplankton samples within layers came from whale feeding station 86-12 and control station 86-13, the only feeding/control stations where horizontal tows were identified to species.

Table 14. Paired comparisons of the biomass of major **zooplankton** groups at presumed whale feeding and control stations, 4-7 September 1986.

Major Group	In Distinct Layer			In Water Column		
	Paired t-value	df	P <sup>a</sup>	Paired t-value	df	Pa
Copepods	1.428	4	0.113	<b>1.652</b>	4	0.087 (*)
<b>Pteropods</b>	-0.771	4	0.758	-0.381	<b>4</b>	0.639
Mysids	1.340	4	0.126	3.587	4	0.012 *
<b>Euphausiids</b>	-0.845	4	0.777	-0.396	4	0.644
<b>Amphipods</b>	0.394	4	0.357	0.472	4	0.331
Fish larvae	-0.130	4	<b>0.549</b>	-0.529	<b>4</b>	0.687
<b>Hydrozoans &amp; Ctenophores</b>	-2.448	4	0.965	1.061	4	0.174
<b>Chaetognaths</b>	<b>-1.158</b>	4	0.844	0.300	4	0.389
<b>Decapod larvae</b>	-0.372	4	0.635	-0.689	4	0.736
<b>Total</b>	<b>1.599</b>	4	0.093 (*)	2.335	4	<b>0.040 *</b>

\*  $0.05 > p > 0.01$  (\*)  $0.1 > p > 0.05$ .

<sup>a</sup>One-tailed tests on logarithmically transformed biomass data.

**Limnocalanus macrurus:** This small copepod, in which adults are <2 mm in length, has been reported from near-surface waters of the marginal seas of the Arctic Ocean (Grainger 1965). In the southeastern Beaufort Sea it is reportedly abundant wherever water of low salinity occurs (Grainger and Grohe 1975), and it is mainly restricted to nearshore shallow waters. Similar results have been obtained in the Alaskan Beaufort Sea (Homer 1981). Johnson (1956) found this species to have estuarine affinities, and suggested that its presence may indicate the spread of river water out over the ocean. Griffiths and Buchanan (1982) found that the biomass of L. macrurus varied widely during a two-season study in the Mackenzie Delta area; it was not a major component of the total copepod biomass in either year.

In 1985, L. macrurus was found in oblique samples at 10 of our 12 stations, but its biomass was significant only at shallow stations on Transects 1 and 4 (Fig. 90; Griffiths et al. 1986, p. 96). In 1986, this species was found in oblique samples from 13 of 18 stations along our four

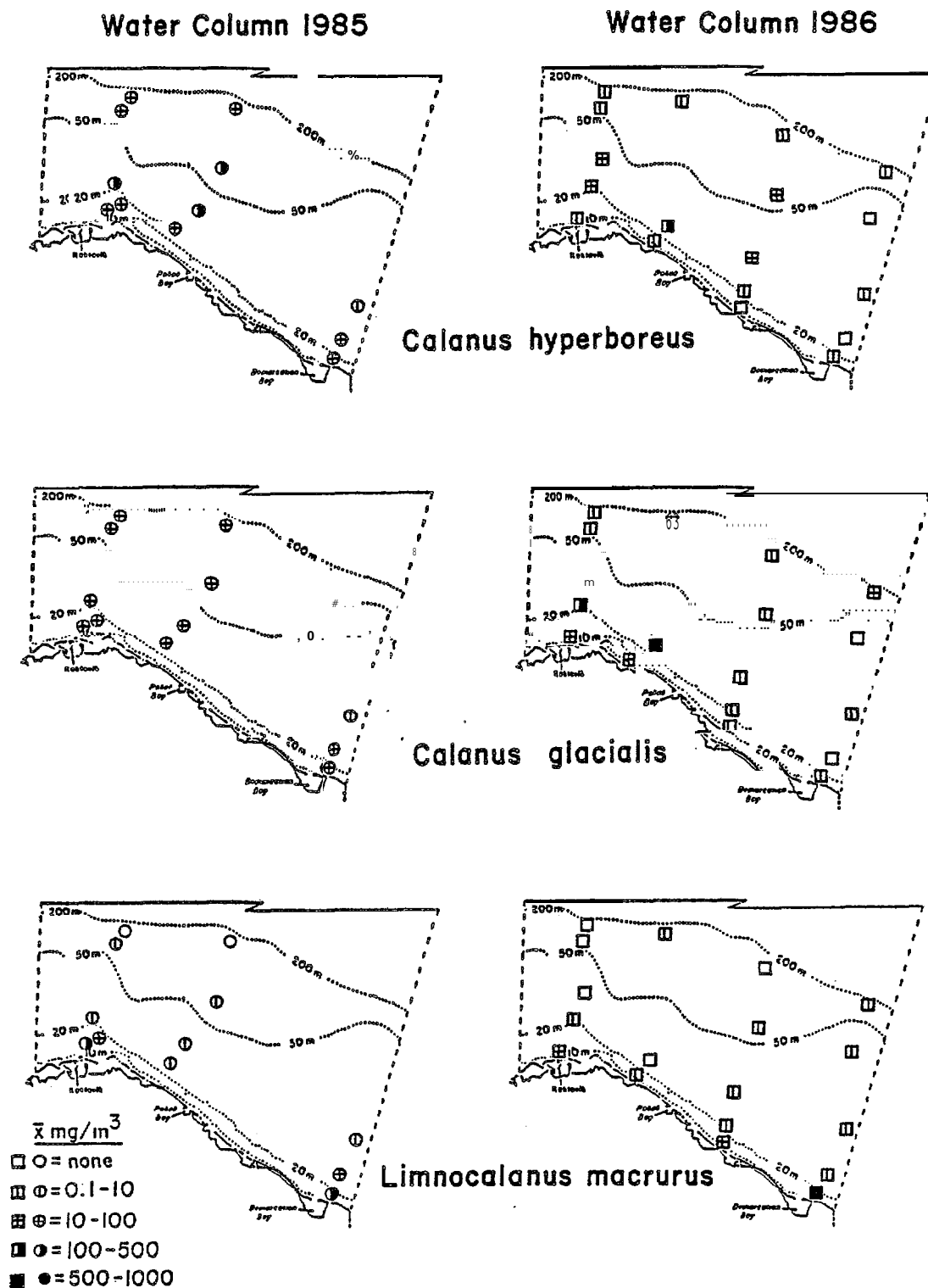


FIGURE 90. Geographic distribution of mean biomass ( $\text{mg}/\text{m}^3$ ) of major copepod species occurring in the water column as a whole along the broad-scale transects in the Eastern Alaskan Beaufort Sea, September 1985 (circles) and 1986 (squares). See Griffiths et al. (1986, p. 96) for additional 1985 data from horizontal tows.

broad-scale transects (Fig. 90). It was generally the dominant copepod at nearshore stations, but was only a minor contributor to total biomass at inner and outer shelf stations. In addition, L. macrurus was the dominant **zooplankter** at bowhead whale feeding stations, accounting for 85% of the total biomass in oblique tows and over 90% of the total in discrete **zooplankton** layers at these locations. This species also was the dominant **zooplankter** near the Yukon coast in August 1985 and early September 1986 (Bradstreet and Fissel 1986; Bradstreet et al. 1987).

The life-cycle of Limnocalanus macrurus is well known in temperate and arctic freshwater systems, but has not been studied in any detail in arctic marine waters. In Georgian Bay, Ontario, L. macrurus has a one-year life cycle. Breeding starts in September and **nauplii** can be found the same month; by the following June over 50% have developed to adults. In Char Lake, NWT, breeding starts in October and peaks in November; **nauplii** become abundant in December and by the following July over 50% have become **adults** (Carter 1969; Roff and Carter 1972). Females do not brood the young; eggs are released directly into the water, sink to the bottom and hatch after a variable resting period, usually less than one month. Development appears to be temperature dependent but even in temperate waters it is not known to produce more than one generation per year (Roff 1972).

Adult males and adult females were by far the dominant life stages of L. macrurus collected in both years of this study (Fig. 91, 92), and along the Yukon coast in 1985 (Bradstreet and Fissel 1986). We found a few copepodite stages III and V in 1985. Similar results were reported by Griffiths and Buchanan (1982), who found that adult males and females and copepodite stage V were the most abundant life stages in late August and September 1980 off the Mackenzie Delta. Only adult females were found during the October 'Polar Star' cruise. Homer and Murphy (1985) found L. macrurus along the Alaskan Beaufort Sea coast in November but found none in March and April. These data suggest that L. macrurus has a one-year life cycle in the nearshore waters of the Beaufort Sea and that adult stages may not survive through the winter. Because the females extrude their eggs directly into the water, one would expect maximum energy content in autumn.

**Calanus hyperboreus:** This species, the largest arctic copepod (4-6 mm long), occurs over most of the southern Beaufort Sea region and constitutes a major element of the **copepod** community (Grainger 1965, 1975). Calanus hyperboreus was the most common copepod reported from bowhead whale stomachs taken in the Kaktovik area (Lowry and Frost 1984) and is common in **zooplankton** samples collected at all distances from shore in that area (Johnson 1956; Homer 1981).

In 1985, C. hyperboreus occurred in oblique samples at all 12 stations. It was the **dominant copepod**, in terms of biomass, at all except the two nearshore stations on Transect 4 and at Station 1 on Transect 1, where it was second in abundance to L. macrurus (Fig. 90). In 1986, C. hyperboreus occurred in oblique samples at 15 of 18 stations along the transects, and was a major contributor to copepod biomass at inner and outer shelf but not nearshore stations. It was the dominant **copepod** only at Stations T3-3 and T3-4 on Transect 3 (Fig. 90). Although present at all bowhead whale feeding stations, it was only a minor contributor there, providing less than 1% of **total** biomass

(Appendix 1). These results were similar to those reported by Bradstreet et al. (1987), who found Calanus hyperboreus to be the dominant copepod in most parts of the Canadian Beaufort Sea, although not along the Yukon coast near feeding bowheads.

The life cycle of Calanus hyperboreus varies from one to two years depending on location. In the Beaufort Sea a two-year cycle is dominant. In 1985, C. hyperboreus biomass was composed primarily of adult females (62%) with lesser contributions from copepodite stages IV (18%) and V (19%). In September 1986, the dominant life stage was copepodite IV (60%), followed by adult females (22%) and copepodite stage V (18%; Fig. 91, 92). In terms of numbers, copepodite IV was the dominant life stage for both years of the study. Adult females accounted for 26% of the numbers in 1985 but only 5% in 1986. The same patterns were apparent for C. hyperboreus collected in the study area during the October cruise of the 'Polar Star' (Fig. 91). This reduced contribution of large females in 1986 may partially account for the decreased importance of C. hyperboreus in the study area in 1986.

**Calanus glacialis:** This species is widely distributed throughout the Arctic Basin and Canadian arctic archipelago in the upper 300 m of the water column (Grainger 1965, 1975; Mohammed and Grainger 1974; Sekerak et al. 1976a; Homer 1979, 1981; Griffiths and Buchanan 1982; Bradstreet and Fissel 1986). This species was the second most common copepod found in stomachs of bowhead whales taken near Kaktovik (Lowry and Frost 1984).

Calanus glacialis was the second most important copepod, in terms of biomass, collected in oblique samples in both years of this study; it occurred at all 12 1985 stations and 16 of 18 1986 stations (Appendix 1; Fig. 90). As with C. hyperboreus, C. glacialis was on average more abundant at inner and outer-shelf stations than at nearshore stations in both 1985 and 1986. This species was collected at all bowhead whale feeding stations but was only a minor contributor to total zooplankton biomass there (<1% of total). C. glacialis was also scarce in oblique plankton samples (6% of total zooplankton biomass) collected in August 1985 off the Yukon coast (Bradstreet and Fissel 1986). It was widespread in the Canadian Beaufort Sea in 1986 (Bradstreet et al. 1987).

The life cycle of C. glacialis appears to be two years in duration in the Arctic Basin. Most individuals spend their first winter as copepodite stage II or III, mature to copepodite Stage V the following summer, and pass the second winter as stage V or adult females (Grainger 1975; Sekerak et al. 1979). In both years of this study, copepodite stages III-V and adult females were the main life stages (Fig. 91, 92). The older and larger life stages (i.e. copepodite stages IV and V; adult females) dominated the biomass, while copepodites III and IV were most abundant numerically.

**Hydrozoans and Ctenophores.**--These taxa, taken together, were typically the second most important group, after copepods, in terms of wet-weight. Two hydrozoans, the jellyfish Aglantha digitale and Halitholus cirratus, plus one ctenophore, Mertensia ovum, accounted for most of this biomass.

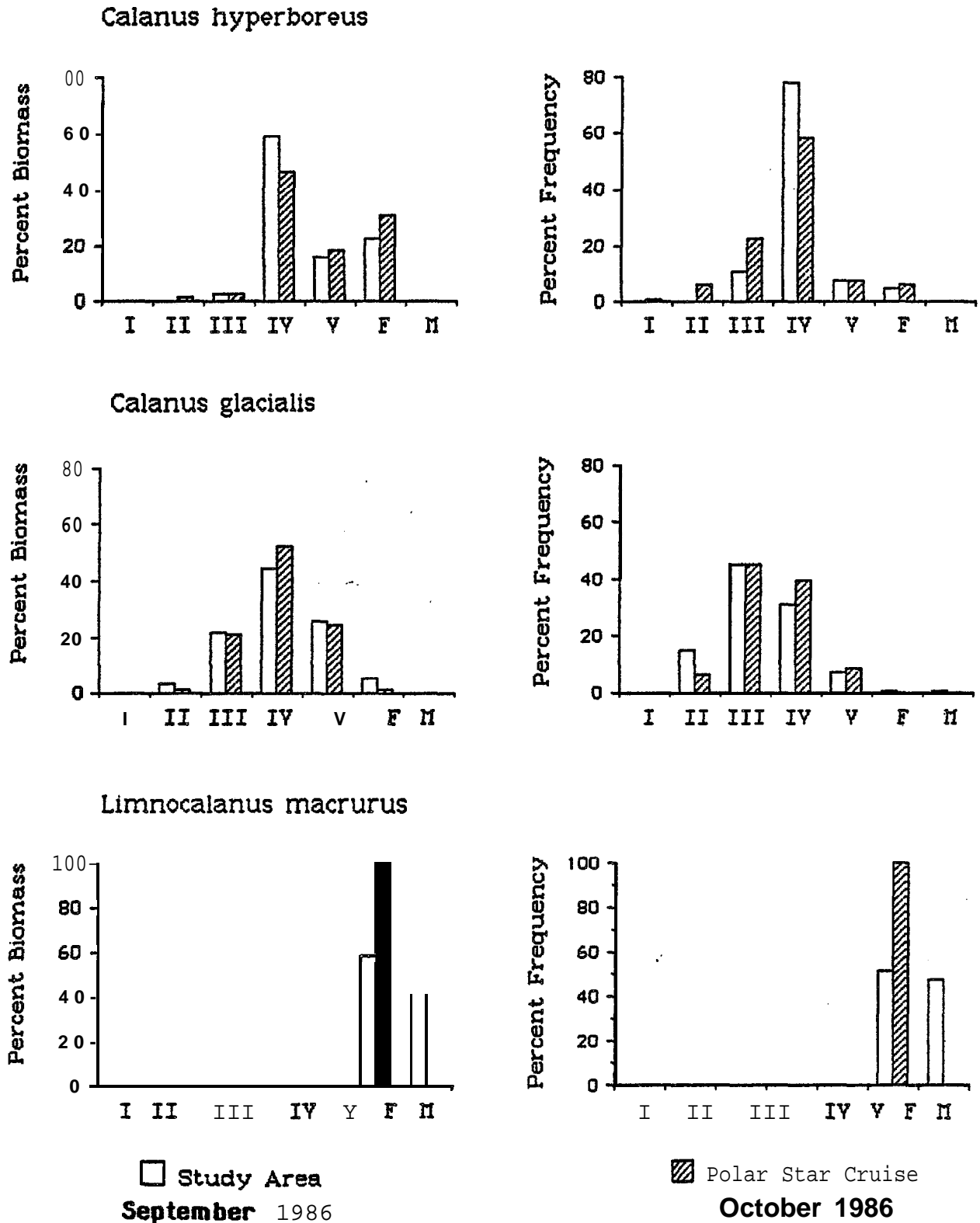


FIGURE 91. Percent contribution of each life-stage to total biomass and total numbers of three major copepod species collected, in oblique tows in the Eastern Alaskan Beaufort Sea, September 1986, and in oblique and vertical tows during the 'Polar Star' cruise, October 1986. I-V denote copepodite stages; F and M denote adult females and males.

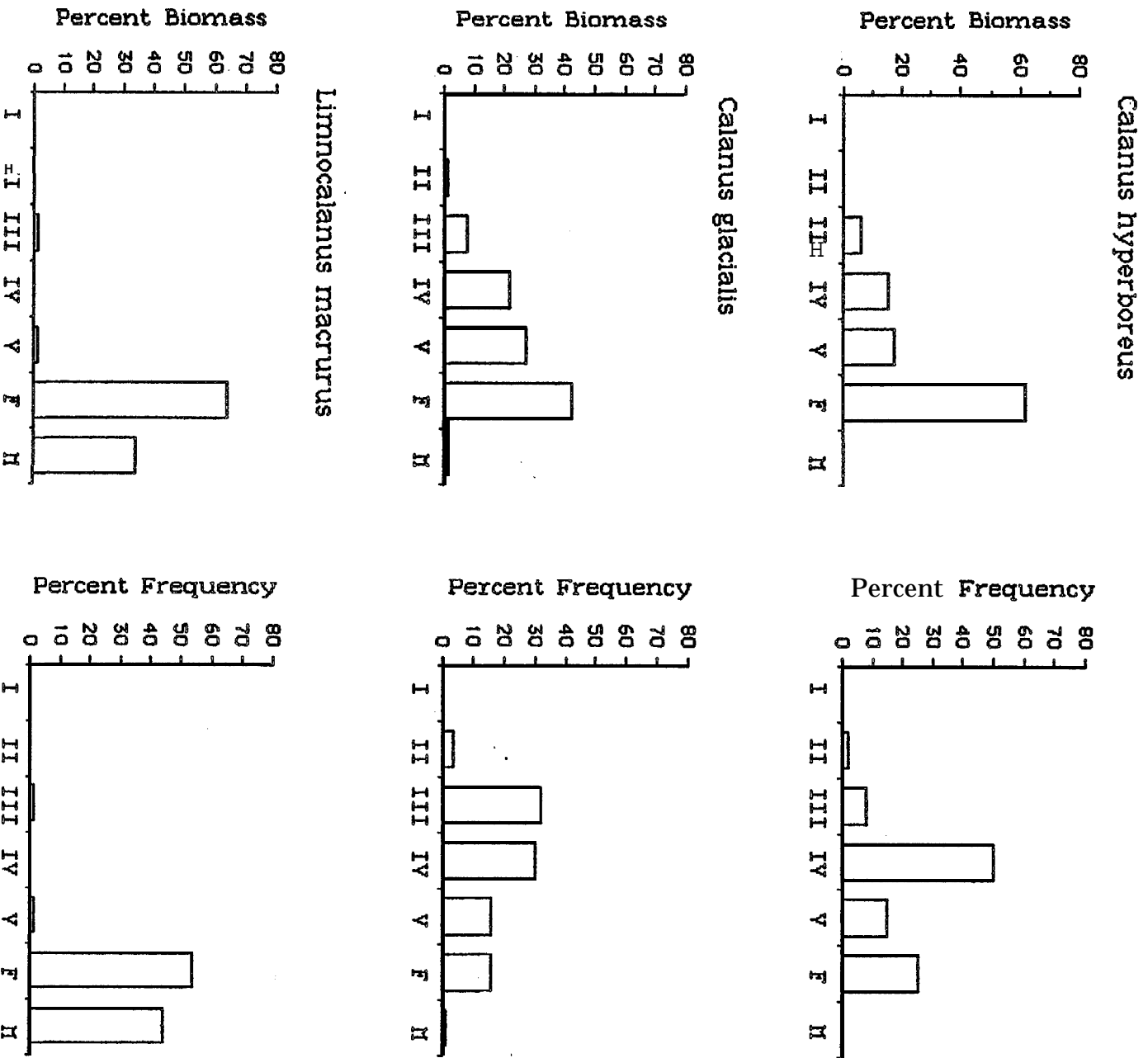


FIGURE 92. Percent contribution of each life-stage to total biomass and total numbers of three major copepod species collected in oblique tows in the Eastern Alaskan Beaufort Sea, September 1985.

**Aglantha digitale:** This jellyfish is one of the most common arctic zooplankters (Grainger 1965). The known arctic distribution of A. digitale (Point Barrow, "southern Beaufort Sea, Jones Sound, Ellesmere Island, Foxe Basin) has been summarized by Shih et al. (1971). It was the major hydrozoan in each part of the Canadian Beaufort Sea sampled by Bradstreet et al. (1987). Homer (1978, 1981) found A. digitale to be a significant component of the zooplankton community, in terms of numbers, within our study area. In 1985, A. digitale was collected at all 12 stations and was a major contributor to the zooplankton biomass below the pycnocline (Griffiths et al. 1986, p. 103). In 1986, A. digitale occurred in oblique tow samples at 17 of 18 stations. However, on average it was not a major component of the zooplankton biomass in the nearshore, inner shelf or outer shelf zones (Appendix 1; Fig. 77 and 93). Similarly, Aglantha digitale, although present, was not an important contributor to total biomass at bowhead feeding stations in September 1986, or at stations across the Alaskan Beaufort Sea during October 1986 (Fig. 81, 89).

**Halitholus cirratus:** This jellyfish has been documented as occurring from point Barrow, Alaska, east to Frobisher Bay, N.W.T. (Dunbar 1942; MacGinitie 1955). Grainger (1965) classified H. cirratus as being primarily coastal and restricted, in the southern Beaufort Sea, to nearshore shallow waters. Griffiths and Buchanan (1982) found this species to comprise a significant portion of the hydrozoan biomass at all stations off the Mackenzie Delta in 1980-81. Low average biomasses were present in each part of the Canadian Beaufort Sea sampled by Bradstreet et al. (1987). In this study, H. cirratus occurred in oblique tow samples from 6 of 12 stations sampled in 1985, and from 8 of 18 stations sampled in 1986 (Appendix 1; Fig. 93). In general, its biomass during both years of the study was greatest at shallow stations, although it was not a major contributor to biomass in the nearshore, inner shelf or outer shelf zones (Fig. 77 and 93). Halitholus cirratus was a significant contributor to biomass, 1.4% of the total, at whale feeding stations in nearshore waters during 1986 (Fig. 89).

**Mertensia ovum:** This ctenophore has been reported from the Chukchi Sea-Point Barrow region east through the southern Beaufort Sea to Frobisher Bay, Baffin Island (Shih et al. 1971). Grainger (1965) reported that M. ovum has a wide temperature-salinity tolerance (-1.5 to 4.0°C; 18-32 psu). This species has not been reported commonly from our study region; Homer (1981) did not record it in the Alaskan Beaufort Sea. Grainger (1965) found it in the southeastern Beaufort Sea in 1951-62, but Grainger (1975) did not report it in the same waters in 1974-1975. Griffiths and Buchanan (1982) did not find any M. ovum off the outer Mackenzie Delta in 1980-1981. However, this species occurred in oblique tow samples at 11 of our 12 stations in 1985, and at 14 of 18 stations in 1986 (Appendix 1; Fig. 93). Mertensia ovum was not a major component of the zooplankton community at bowhead whale feeding stations in 1986. It was, however, a significant contributor to total zooplankton biomass in vertical tow samples collected in the top 50 m of deep waters in the study area in October 1986 (Fig. 81).

**Amphipods.** --Amphipods occurred in the stomachs of all eight bowhead whales examined in 1979-82 at Kaktovik, Alaska; however, in none of the whales did they form over 3% of the stomach contents (Lowry and Frost 1984). In our study, amphipods were generally only minor contributors to zooplankton biomass



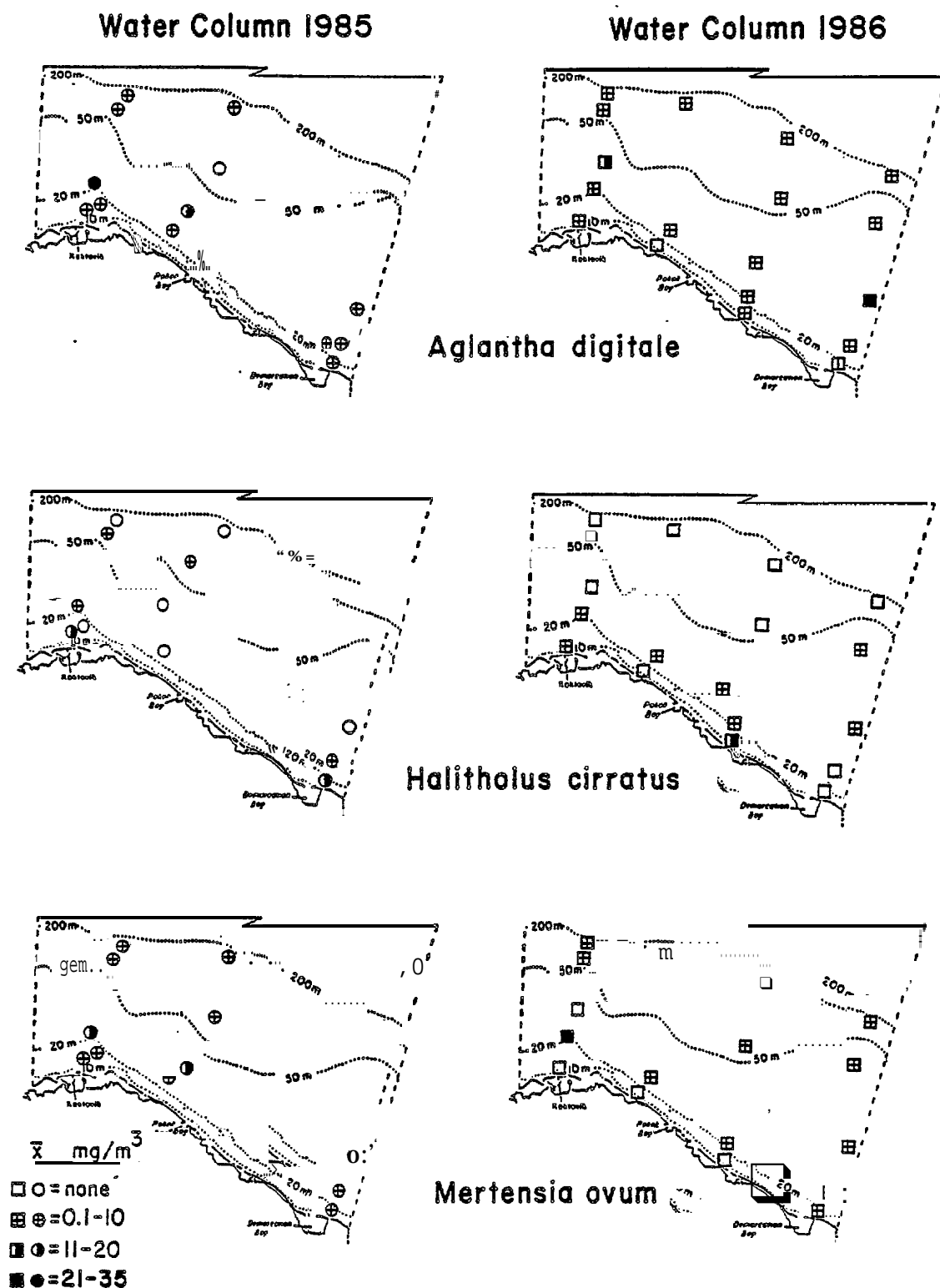


FIGURE 93. Geographic distribution of mean biomass (mg/m<sup>3</sup>) of major hydrozoan and ctenophore species occurring in the water column as a whole along the broad-scale transects in the Eastern Alaskan Beaufort Sea, September 1985 (circles) and 1986 (squares). Note differences in scale from that used for copepods (cf. Fig. 90). See Griffiths et al. (1986, p. 103) for additional 1985 data from horizontal tows.

along broad-scale transects and in whale feeding areas. In this study, Parathemisto libellula accounted for most amphipod biomass.

**Parathemisto libellula:** This circumpolar species is also found in the Pacific Ocean and the Bering and Okhotsk seas, and it is known to occur in our study area (Homer 1981). Parathemisto libellula is the largest member of the genus (up to 60 mm in length) and has a two-year life cycle in arctic waters (Shoemaker 1955; Dunbar 1957). Late in the winter, males mature at lengths of 19-21 mm and females at 21-25 mm (Wing 1976). The species is predominantly carnivorous but also ingests some vegetable matter (Dunbar 1946). Parathemisto libellula was found in the stomachs of six of eight bowheads harvested at Kaktovik, but it and other less common hyperiid amphipods accounted for only 0.1% of their stomach contents by volume (Lowry and Frost 1984).

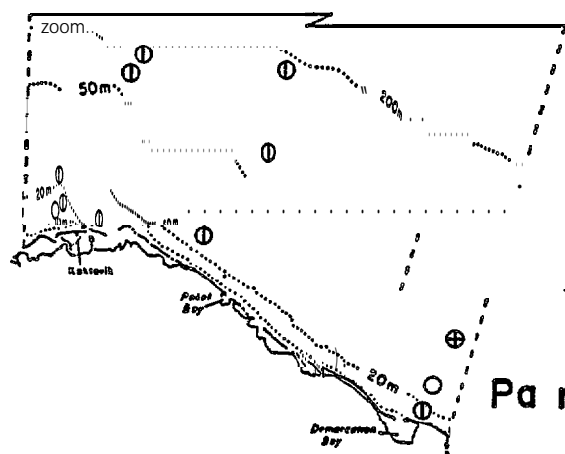
Along our broad-scale transects, P. libellula was found in oblique tow samples taken at 10 of 12 stations in 1985 and at 13 of 18 stations in 1986 (Appendix 1; Fig. 94). In 1985, this species showed no consistent distribution pattern. In 1986, it was not found at the most nearshore stations (Fig. 94). Similarly, it was only a minor contributor to total zooplankton biomass at whale feeding and control stations in nearshore waters in 1986. This species was not found in the top 50 m of the water column in the official study area during October 1986 (Fig. 81). Most P. libellula collected in both years were first-year individuals and not yet sexually mature.

Mysids and Euphausiids. --Mysids and euphausiids appear to be important food items in the diets of some bowhead whales in the Alaskan Beaufort Sea (Lowry and Frost 1984; Lowry et al. 1987). Mysis litoralis and Thysanoessa raschii were the only important members of the two groups, in terms of biomass, during this study.

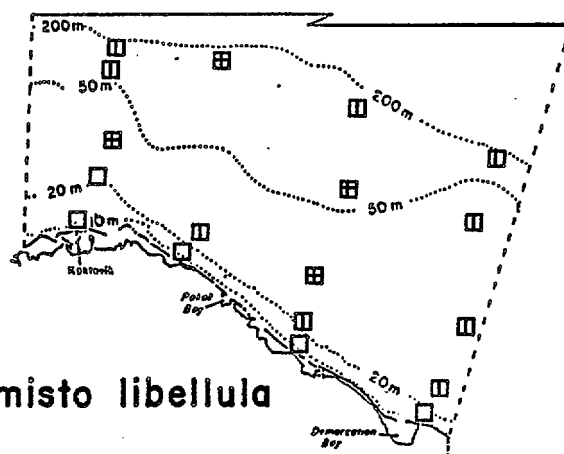
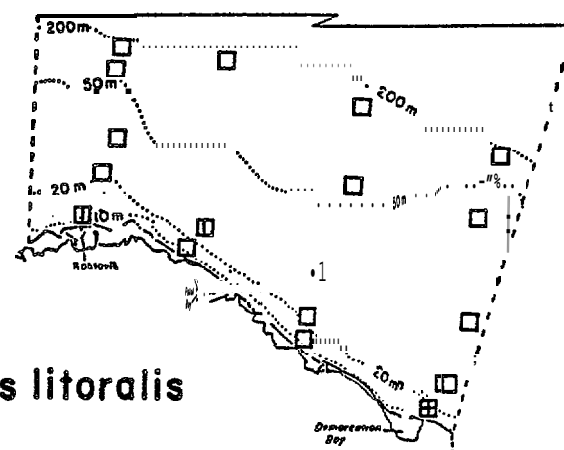
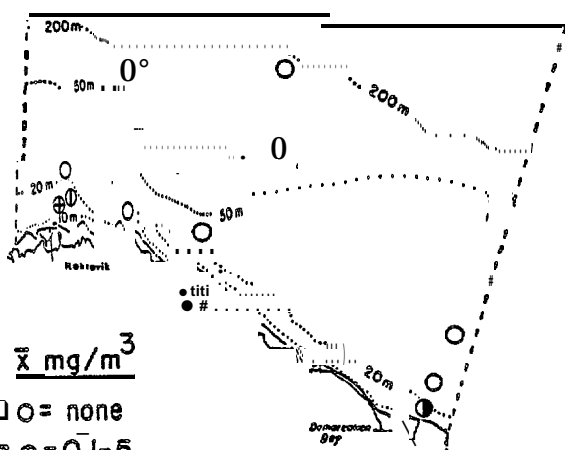
**Mysis litoralis:** This species is common in nearshore shallow waters in the Alaskan and Canadian Beaufort Sea, including our study area (Broad et al. 1980; Griffiths and Dillinger 1981; Homer 1981; Griffiths and Buchanan 1982; Jewett et al. 1984; Bradstreet and Fissel 1986). In 1985, M. litoralis was found in oblique tow samples from only 3 of 12 stations, all in nearshore or inner shelf waters. In 1986, it was found in oblique tows from only 3 of 18 stations along broad-scale transects, all in the nearshore zone (Appendix 1; Fig. 94). Most mysids taken in horizontal tows were taken near the bottom (Fig. 76, 78; Griffiths et al. 1986, p. 105). It was also found at 4 of 5 whale feeding stations and one of the control stations, all in shallow waters. Mysis litoralis was common at some whale feeding stations in 1986 (Fig. 89). It was not found in the upper 50 m of the water column at mid-shelf and deep stations during October 1986. The apparent absence of M. litoralis from deeper inner and outer shelf waters may have been real, or it may have been due to the few samples taken near the bottom at these stations.

**Thysanoessa raschii:** This euphausiid is common in the Arctic Basin beyond the continental shelf, and has been reported in the Alaskan and Canadian Beaufort Sea and over the continental shelf of the Chukchi and Barents seas (Geiger et al. 1968; Homer 1978, 1979, 1981; Broad et al. 1980). In August 1985, euphausiids, primarily Thysanoessa raschii, comprised 1.0% of the total zooplankton biomass in oblique samples taken off the Yukon Coast in the Canadian Beaufort Sea (Bradstreet and Fissel 1986). Thysanoessa raschii

## Water Column 1985



## Water Column 1986

*Parathemisto libellula**Mysis litoralis* $\bar{x} \text{ mg/m}^3$ 

- ○ = none
- ▣ ○ = 0.1-5
- ▤ ⊕ = 6-20
- @ = 21-40
- ● = 41-60

FIGURE 94. Geographic distribution of mean biomass ( $\text{mg/m}^3$ ) of major amphipod and mysid species occurring in the water column as a whole along the broad-scale transects in the Eastern Alaskan Beaufort Sea, September 1985 (circles) and 1986 (squares). Note differences in scale from that used for earlier similar maps. See Griffiths et al. (1986, p. 105) for additional 1985 data from horizontal tows.

was found commonly in the stomachs of bowhead whales taken near **Kaktovik** and **Point Barrow** (Lowry and Frost 1984). During oblique sampling along our broad-scale transects, T. raschii was collected at 8 of 12 stations in 1985 and at 5 of 18 stations in 1986 (Appendix 1; Fig. 95). Although not a major contributor to total zooplankton biomass, this species was found at 3 of 5 whale feeding stations sampled in 1986. Along the four 1986 transects, Thysanoessa raschii occurred mainly at the deeper nearshore and inner shelf stations. T. raschii was abundant in the Western Alaskan Beaufort Sea in **October** 1986, but was uncommon in the official study area during the same period. Similarly, its apparent abundance in the Canadian Beaufort declined from west to east in 1986 (Bradstreet et al. 1987). All of these results should be interpreted cautiously, given the known tendencies of euphausiids to concentrate in dense patches and to avoid approaching sampling gear.

Fish Larvae.--Three groups of larval fish were collected in the study area in 1985 and 1986: **Gadids**, **Liparids**, and **Cottids**. Only Gadids, represented by the Arctic cod, Boreogadus saida, were a major contributor to the zooplankton biomass in either year.

**Boreogadus saida**: This species occurs throughout the marine waters of northern North America, including the northern Bering Sea, northern Alaska, the Canadian arctic islands, and south to the Grand Banks (Craig et al. 1982; Bradstreet et al. 1986). It "has been reported as far north as 88°N in the Arctic Ocean. During oblique sampling along our broad-scale transects, B. saida was found at 10 of 12 stations in 1985, and at 13 of 18 stations in 1986 (Appendix 1; Fig. 95). There was no obvious pattern to its 1985 distribution, but in 1986 it was absent from the most nearshore stations (Fig. 95). Although it was widely distributed, B. saida generally was not a major contributor to total zooplankton biomass along the transects in September 1985 and 1986, or at whale feeding or control stations in 1986. Boreogadus saida also was only a minor contributor to zooplankton biomass in the top 50 m of the water column at stations over deep water during October 1986 (Fig. 81).

#### Echosounder Surveys of Zooplankton Biomass

**Hydroacoustic** surveys at individual stations and along transects provided data on zooplankton at far more locations and depths than could be sampled by traditional net-sampling methods. The hydroacoustic volume scattering data (VS) collected at stations and along transects were converted to estimates of total zooplankton biomass using the regression relationships developed above (see 'Acoustic Biomass vs. Net Biomass' subsection, p. 169-171). The results from broad-scale transects were then used to investigate (1) the vertical distribution of estimated zooplankton biomass at individual stations, (2) the depth-integrated horizontal distribution of zooplankton, and (3) zooplankton patchiness. Comparable data from shorter transects near feeding whales were presented earlier, in the 'Zooplankton in Whale Feeding Areas' subsection (Fig. 83-87; p. 187-198).

Vertical Distribution.--Studies in other areas have shown that the vertical and horizontal distributions of zooplankton in the water column are patchy and dynamic in nature (Mackas et al. 1985). They can be affected by numerous factors including, but not limited to, light intensity, food availability, temperature and salinity. Typically, zooplankton is concentrated

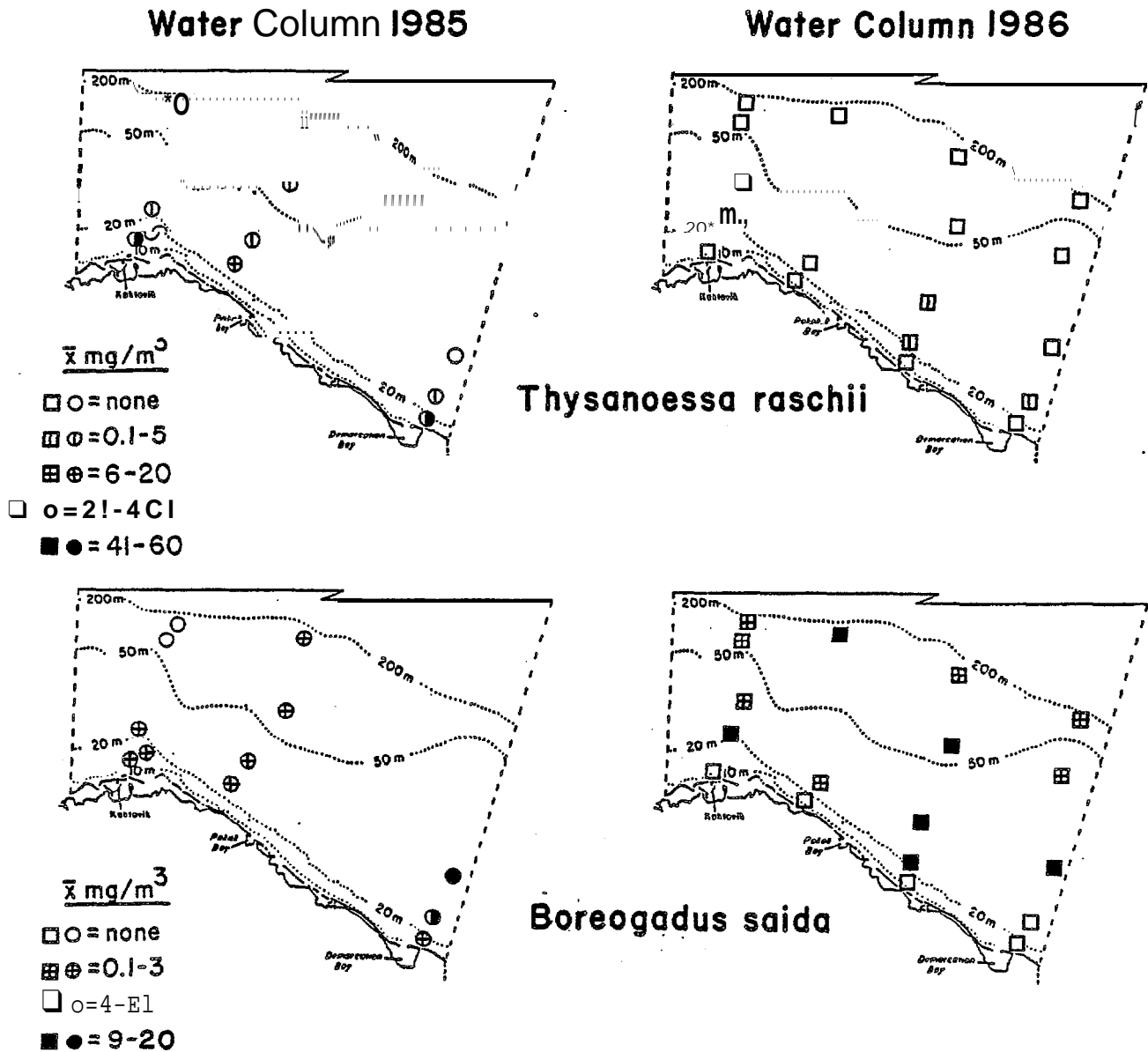


FIGURE 95. Geographic distribution of mean biomass ( $\text{mg/m}^3$ ) of major euphausiids and fish larvae occurring in the water column as a whole along the broad-scale transects in the Eastern Alaskan Beaufort Sea, September 1985 (circles) and 1986 (squares). Note differences in scale from that used for earlier similar maps. See Griffiths et al. (1986, p. 106) for additional 1985 data from horizontal tows.

in patches or layers **that** can vary widely in both horizontal extent (from 10s to **1000s** of meters) and **thickness** (from centimeters to **10s** of meters).

**1985 Results:** The vertical distributions of estimated **zooplankton** biomass in the region during September 1985 were described by **Griffiths et al.** (1986, p. 114-116). Typically, from one to three layers were evident at each station along the two extended transects. Most of these **zooplankton** layers were 5 to 8 m thick and most were found in the upper 35 m of the water column. Only in shallow nearshore areas (water depth <25 m) did they occur through the entire water column. Biomasses within layers were typically 300-1450  $\text{mg}/\text{m}^3$ , although lower **values** were found in some layers in outer **shelf** waters. Between these dense layers the estimated **total** biomass below the **pycnocline** was **typically** 100-300  $\text{mg}/\text{m}^3$ . In September of 1985, most if not all concentrations of **zooplankton** in the region were **close** enough to the surface to have been easily accessible to feeding bowhead whales.

**1986 Results:** In September 1986, VS data from depths below the **pycnocline** showed from one to three layers at each station in the study area (Fig. 96).

At stations in shallow waters (<34 m depth; Stations 1 and 2 along each transect), zooplankton layers 2 to 8 m thick occurred at various depths throughout the water column. A total of 11 major **zooplankton** layers (biomass >400  $\text{mg}/\text{m}^3$ ) were recognized at the eight stations, excluding layers at or near the **pycnocline** (Fig. 96). Within the 11 layers, estimated biomass ranged from 400 to greater than 1600  $\text{mg}/\text{m}^3$ . The estimated zooplankton biomass was at least 200 to 300  $\text{mg}/\text{m}^3$  at virtually all depths below the **pycnocline**. These results are similar to those from 1985 shallow water **stations**, where **peak biomasses** in layers ranged from 400 to 1450  $\text{mg}/\text{m}^3$  and exceeded 300  $\text{mg}/\text{m}^3$  at most depths (**Griffiths et al.** 1986). **Thus**, at shallow water stations during both years of the study, significant amounts of **zooplankton** were available at most depths **below** the **pycnocline**.

At stations in intermediate depths (35 to 45 m depth; Station 3 along Transects T1, T3, and T4), **zooplankton** layers occurred at scattered depths (Fig. 96). About eight major layers were evident at the three stations; they were at depths 10 to 45 m. Estimated biomass within the layers ranged up to 1550  $\text{mg}/\text{m}^3$ , while between the **layers** biomass varied from 150 to 350  $\text{mg}/\text{m}^3$  (Fig. 96). Likewise in 1985 estimated total **biomasses** at stations in similar **water** depths were 300 to 1100  $\text{mg}/\text{m}^3$  within layers and 150 to 300  $\text{mg}/\text{m}^3$  between **layers** (**Griffiths et al.** 1986, p. 114).

In deeper waters (>50 m), major **zooplankton** layers were scattered throughout the water column only at Stations 4, not at Stations 5 (Fig. 96). These layers varied in thickness from about 5 m to over 20 m (Fig. 96). Within the recognized layers at Stations T1-4, T3-4, and T4-4, estimated **zooplankton** biomass ranged up to 1000  $\text{mg}/\text{m}^3$ , while outside the layers it varied from 150 to 300  $\text{mg}/\text{m}^3$ . At the deepest stations, estimated biomass was relatively uniform over a wide range of depths, typically 250  $\text{mg}/\text{m}^3$  at Station T1-5 and <100  $\text{mg}/\text{m}^3$  at Stations T3-5 and T4-5 (Fig. 96). The estimates of **zooplankton** biomass at Station T1-5 should be viewed with some caution since most of the **water column** consisted of Bering Sea Water and physical gradients may have produced artificially high readings. In 1985, the estimated biomasses in

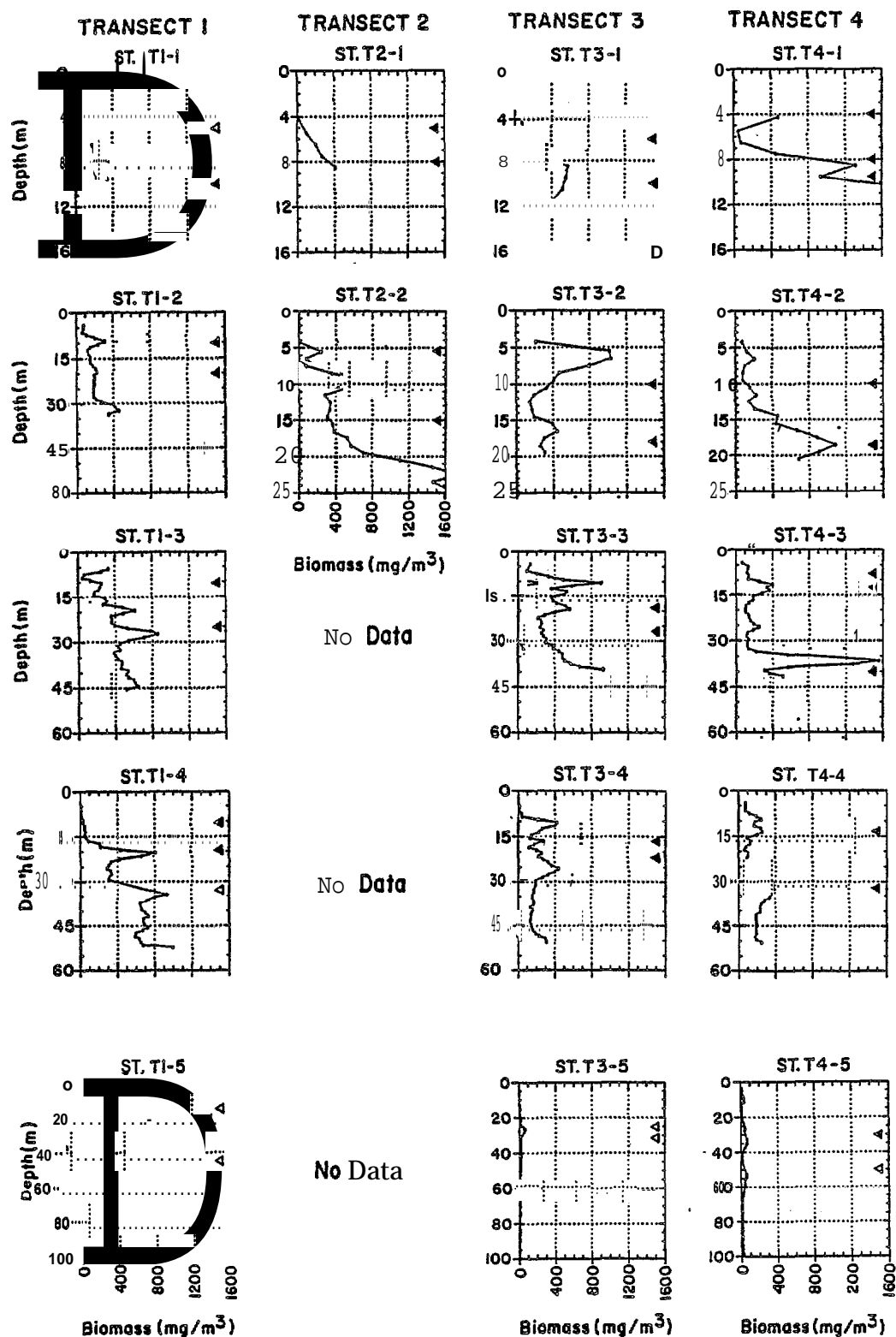


FIGURE 96. Vertical distributions of estimated zooplankton biomass at stations along broad-scale transects, September 1986, based on 200 kHz echosounder data. All acoustic data collected at a given station were averaged. Depth scales are corrected for transducer depth. Triangles show depths at which horizontal tows were taken; open triangles indicate tows taken at pycnoclines. See Griffiths et al. (1986, p. 115) for corresponding 1985 data.

**layers** at the deep stations were somewhat **lower**, 150 to 800  $\text{mg}/\text{m}^3$ . Values between layers were 100 to 150  $\text{mg}/\text{m}^3$  (Griffiths et al. 1986, p. 114-116). Considering both years, the major **zooplankton** layers ( $>400 \text{ mg}/\text{m}^3$ ) found in waters  $>50 \text{ m}$  deep were all at depths of 10 to 50 m.

**Summary**, 1985-86: The vertical distributions of zooplankton biomass were similar in both years. Throughout **the** study area, most zooplankton layers were 5 to 8 m thick. Most dense **zooplankton** layers were in the upper 45 m of the water column. At some shallow water stations ( $<25 \text{ m}$  depth) the zooplankton layers occurred throughout most of the water column, extending all the way to the bottom. **Since** most concentrations of **zooplankton** were  $<45 \text{ m}$  below the surface during both years, even where water depth was over 100 m, **most zooplankton** would be easily accessible to feeding bowhead whales. The **echosounder** did not measure zooplankton biomass in surface waters, but net tows showed that there was little **zooplankton** above the **pycnocline**.

Horizontal Distribution.--The depth-integrated horizontal distributions of estimated zooplankton biomass along each transect are shown in Figure 97. Comparable data from 1985 are shown in **Griffiths** et al. (1986, p. 116-117).

1985 Results: Along Transects 1 and 2 the mean biomass appeared to decrease with increasing water depth and distance from shore. Over the inner continental shelf, depth-integrated **biomasses** were relatively **high** but variable, 300 to 1500  $\text{mg}/\text{m}^3$  along Transect 1, and 100 to 2000  $\text{mg}/\text{m}^3$  along Transect 2. Over the outer shelf, estimated mean biomass tended to be lower and more uniform (Transect 1, 40 to 300  $\text{mg}/\text{m}^3$ ; Transect 2, 120 to 480  $\text{mg}/\text{m}^3$ ).

**1986 Results**: Along Transect T1, average **biomasses** were relatively uniform over the nearshore and inner shelf waters between Stations T1-1 and T1-4, ranging from 150 to 350  $\text{mg}/\text{m}^3$ . Along the outer portion of this transect apparent **biomasses** were higher, reaching 600  $\text{mg}/\text{m}^3$  (Fig. 97). The seemingly higher **biomasses** at the end of the transect, where Bering Sea Water was present, may have been partially an artifact of density gradient interference.

Along Transect T2, the average estimated **biomasses** varied widely, **but** were highest in the nearshore zone near Station T2-2 (range 150 to 650  $\text{mg}/\text{m}^3$ ). Thereafter, **biomasses** tended to decrease with increasing distance from shore and increasing depth (Fig. 97).

Along Transect T3, the estimated **zooplankton biomasses** were variable. They ranged from 200 to 550  $\text{mg}/\text{m}^3$  in the nearshore zone, increased to a maximum of 750  $\text{mg}/\text{m}^3$  over the inner shelf, and then decreased to lower levels (150 to 300  $\text{mg}/\text{m}^3$ ) in outer shelf waters (Fig. 97).

Along Transect T4, average **biomasses** varied widely, particularly in the nearshore zone (175 to 1200  $\text{mg}/\text{m}^3$ ). Over the inner and outer shelf, estimated **biomasses** showed peaks of 400 to 600  $\text{mg}/\text{m}^3$ , but generally were less than 300  $\text{mg}/\text{m}^3$ . The lowest **biomasses** were found over the deepest depths (Fig. 97).

In the nearshore zone, the highest zooplankton **biomasses** were typically **close** to the bottom (depth range 10 to 30 m; Fig. 98). Over the inner shelf, the maximum **zooplankton biomasses** were either close to the bottom or about 20 to 30 m deep, varying from point to point along each transect (Fig. 98). Over



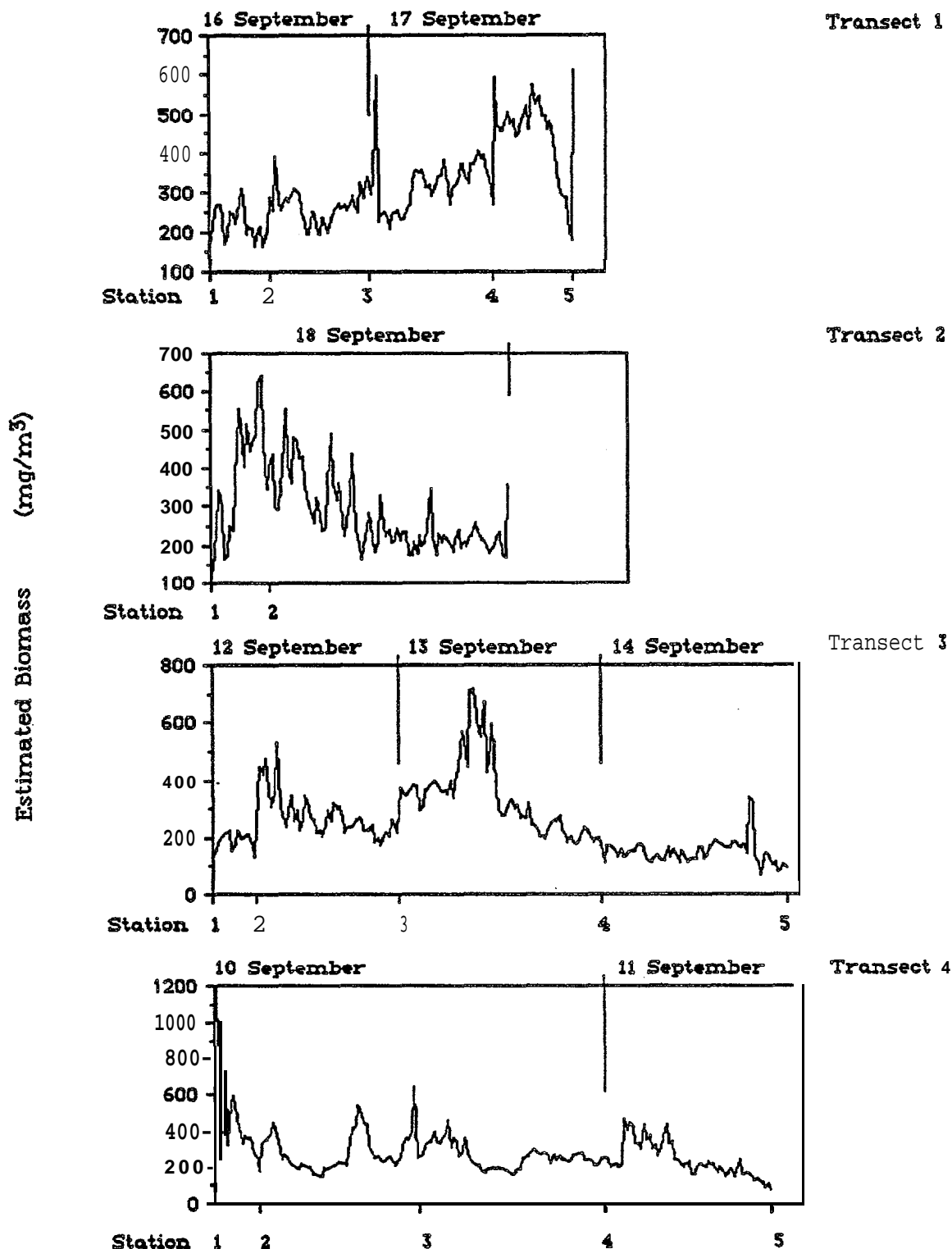
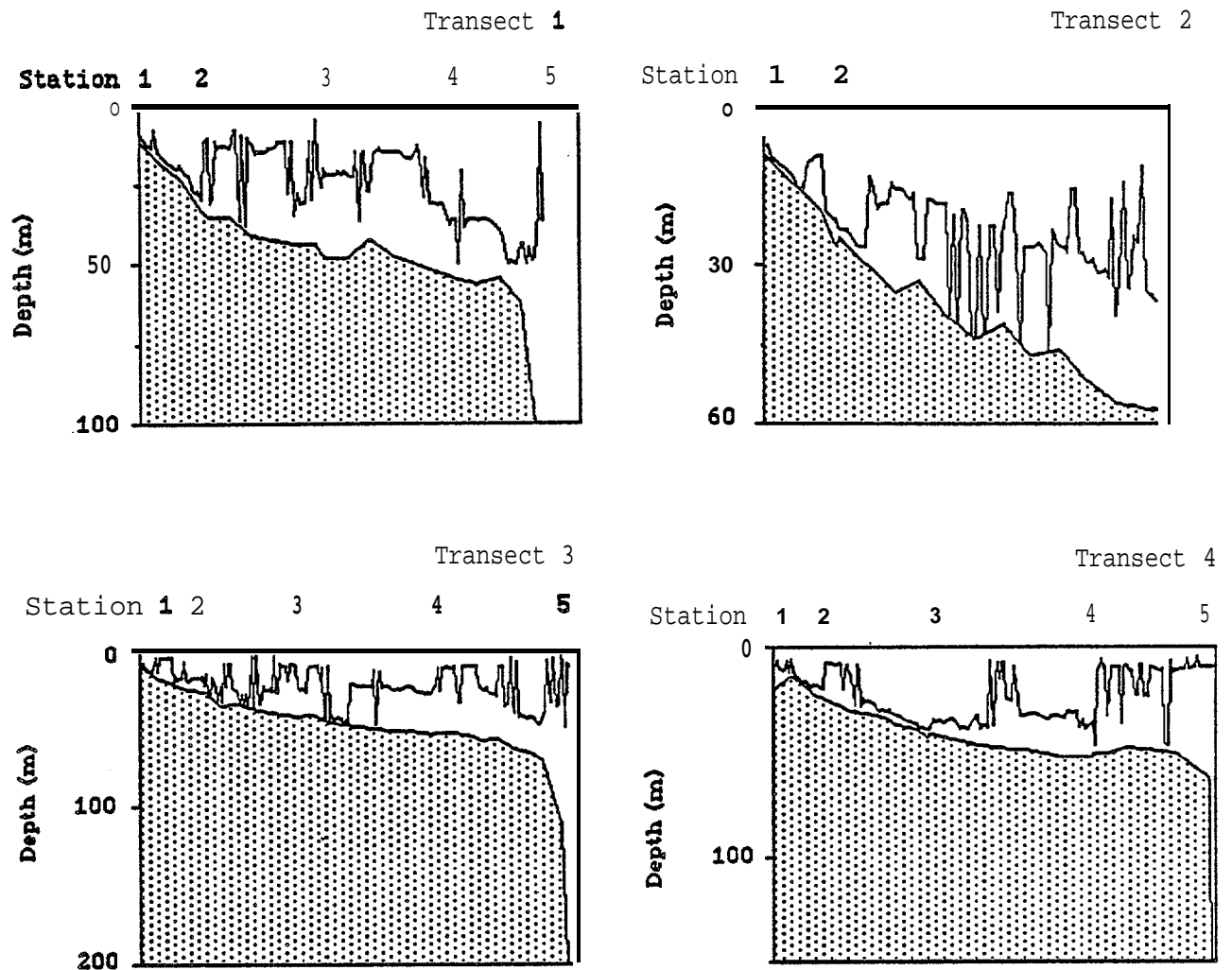


FIGURE 97. Horizontal distribution of estimated zooplankton biomass ( $\text{mg}/\text{m}^3$ ) along each 1986 broad-scale transect. Data from the 200 kHz echosounder were depth integrated by 2-rein intervals (approx. 365 m horizontally) and for depths from just below the pycnocline to 50 m (or bottom if <50 m). No data available for outer shelf portion of Transect T2. See Griffiths et al. (1986, p. 117) for corresponding 1985 data.



**FIGURE 98.** Depths of maximum zooplankton biomass for each 2-rein time interval (approx. 365 m) along the 1986 broad-scale transects. Data are from the 200 kHz echosounder. Stippled area indicates the bottom. See Griffiths et al. (1986, p. 118) for corresponding 1985 data.

the outer shelf, the highest zooplankton biomasses were between 25 and 35 m on Transect T1 and between 10 and 40 m depth on Transects T3 and T4 (Fig. 98). No echosounder data were available for the outer shelf zone of Transect 2.

**Summary, 1985-86:** Echosounder surveys showed that zooplankton biomass was generally highest in the nearshore zone and tended to decrease with increasing distance from shore and increasing depth. The two notable exceptions were the outer shelf zone of 1986 Transect T1 (possibly an artifact) and the inner shelf region of 1986 Transect T3. Although no echosounder data were collected beyond the 200 m contour in 1985 or 1986, net sampling over water depths up to 2000 m during October 1986 showed that biomasses in the top 50 m far offshore were low.

Maximum zooplankton biomasses occurred near the bottom (depth range 10 to 30 m) in the nearshore zone and often in the inner shelf zone as well. Elsewhere in the inner shelf zone, and at all places over the outer shelf, the depths of maximum zooplankton biomass were 10 to 40 m.

**Zooplankton Patchiness.** --Zooplankton patchiness was determined along each of four broad-scale transects surveyed in 1986 and two of those surveyed in 1985 (Fig. 99, 100). The 1986 data are for the depth range 4 to 50 m; no hydroacoustic data are available from the surface layer (0 to 4 m depth). It should be noted that the biomass categories represented by the contours are arbitrary. Although the edges of the zooplankton patches appear abrupt because of the biomass categories selected; the edges were actually rather diffuse. Also, the locations of 1985 Transects 1 and 2 were not quite the same as those for 1986 Transects T1 and T2, and they were not sampled at quite the same time in September.

**1985 Results:** Along Transect 1 zooplankton patches were more abundant in nearshore and inner shelf water masses (depths <40 m) than in the outer shelf waters (depths >50 m). Almost all zooplankton patches in the outer shelf waters of Transects 1 and 2 were within the top 35 to 40 m (Fig. 99). Although the sizes of patches varied, most were quite extensive horizontally (i.e. 1000's of meters in length) and 5 to 10 m thick. The highest biomasses were generally just below the pycnocline (Griffiths et al. 1986, p. 119-123).

**1986 Results:** Along Transect T1, most zooplankton patches occurred at depths between 10 and 40 m within the nearshore, inner and outer shelf zones (Fig. 100A). In the nearshore region, between Stations T1-1 and T1-3, only a few small zooplankton patches with density >1000 mg/m<sup>3</sup> were evident. One was located near the bottom (16 to 20 m depth) between Stations T1-1 and T1-2, and some smaller ones were found at various depths in the water column near Station T1-3 (Fig. 100A). The largest of these patches with biomass >1000 mg/m<sup>3</sup> was only 0.5 km in length and 2 to 3 m in depth. There were more extensive patches containing 500 to 1000 mg/m<sup>3</sup> scattered throughout the nearshore zone, although at most depths the biomass was 100 to 500 mg/m<sup>3</sup> (Fig. 100A). The top 6 m of the water column generally contained little zooplankton (<100 mg/m<sup>3</sup>), based on the hydroacoustic and surface tow data.

In waters over the inner shelf, between Stations T1-3 and T1-4, patches of zooplankton with density >1000 mg/m<sup>3</sup> were sparse; however, patches with 500-1000 mg/m<sup>3</sup> were more extensive and larger than in the nearshore zone (up

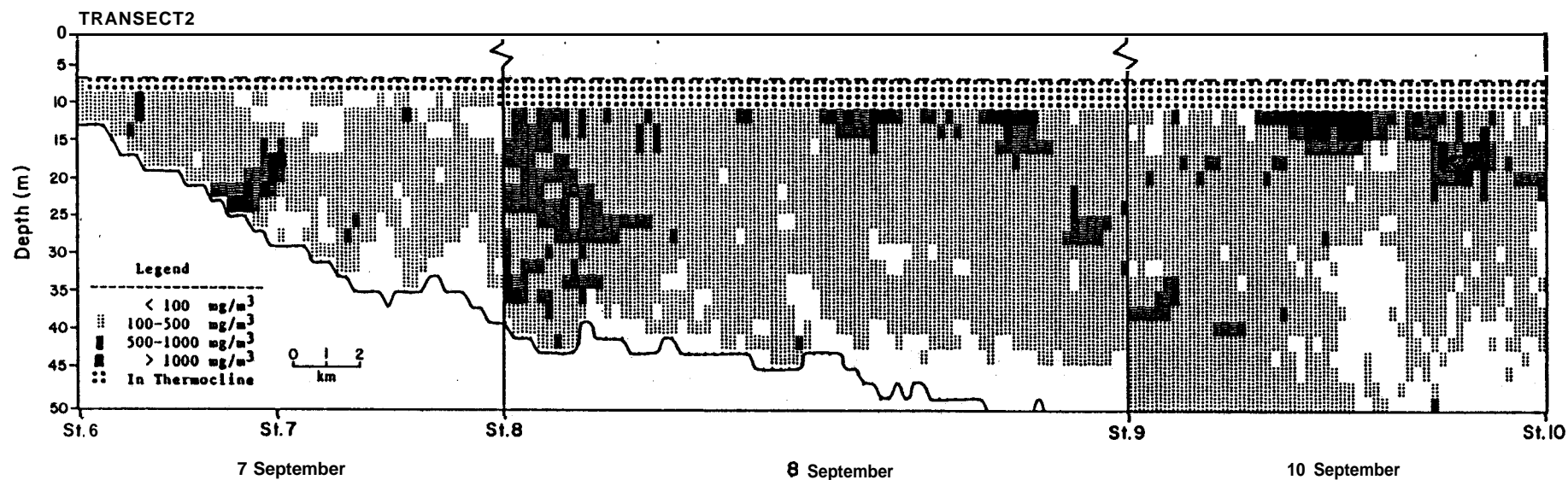
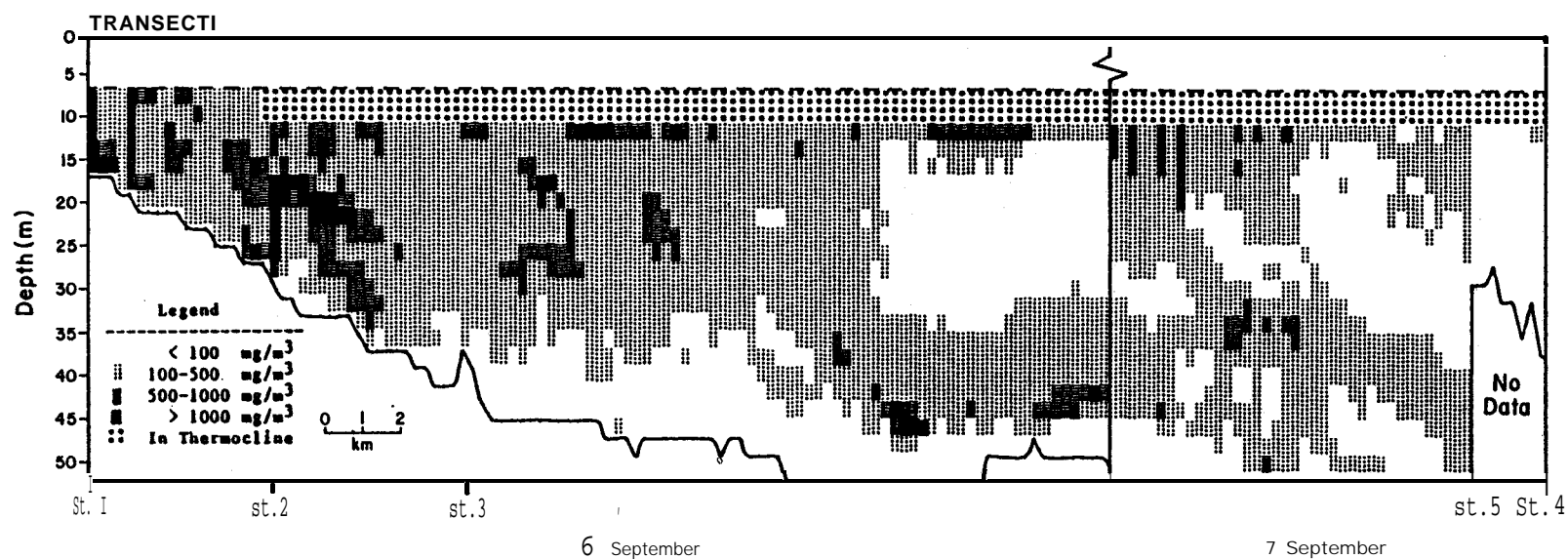


FIGURE 99. Zooplankton patchiness, estimated from continuous hydroacoustic sampling data along 1985 Transects 1 and 2. Data recorded within and above the thermocline are excluded. Jagged vertical line indicates change in date. Note that the horizontal scale is very much compressed relative to the vertical scale.

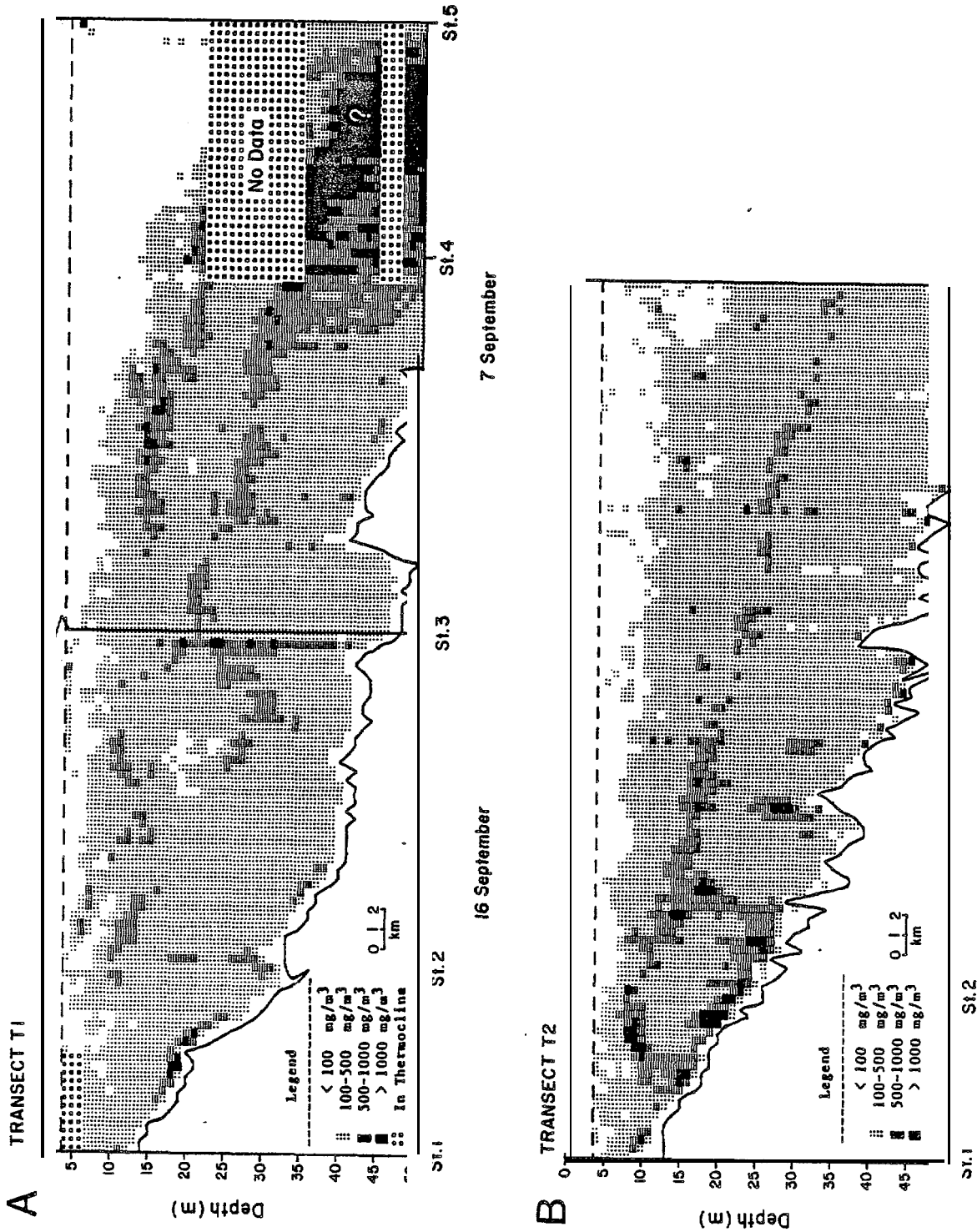


FIGURE 100. Zooplankton patchiness, estimated from continuous hydroacoustic sampling along 1986 Transects T1 and T2. Data recorded within and above thermoclines are excluded. Jagged vertical line indicates change in date. Note that the horizontal scale is very much compressed relative to the vertical scale.

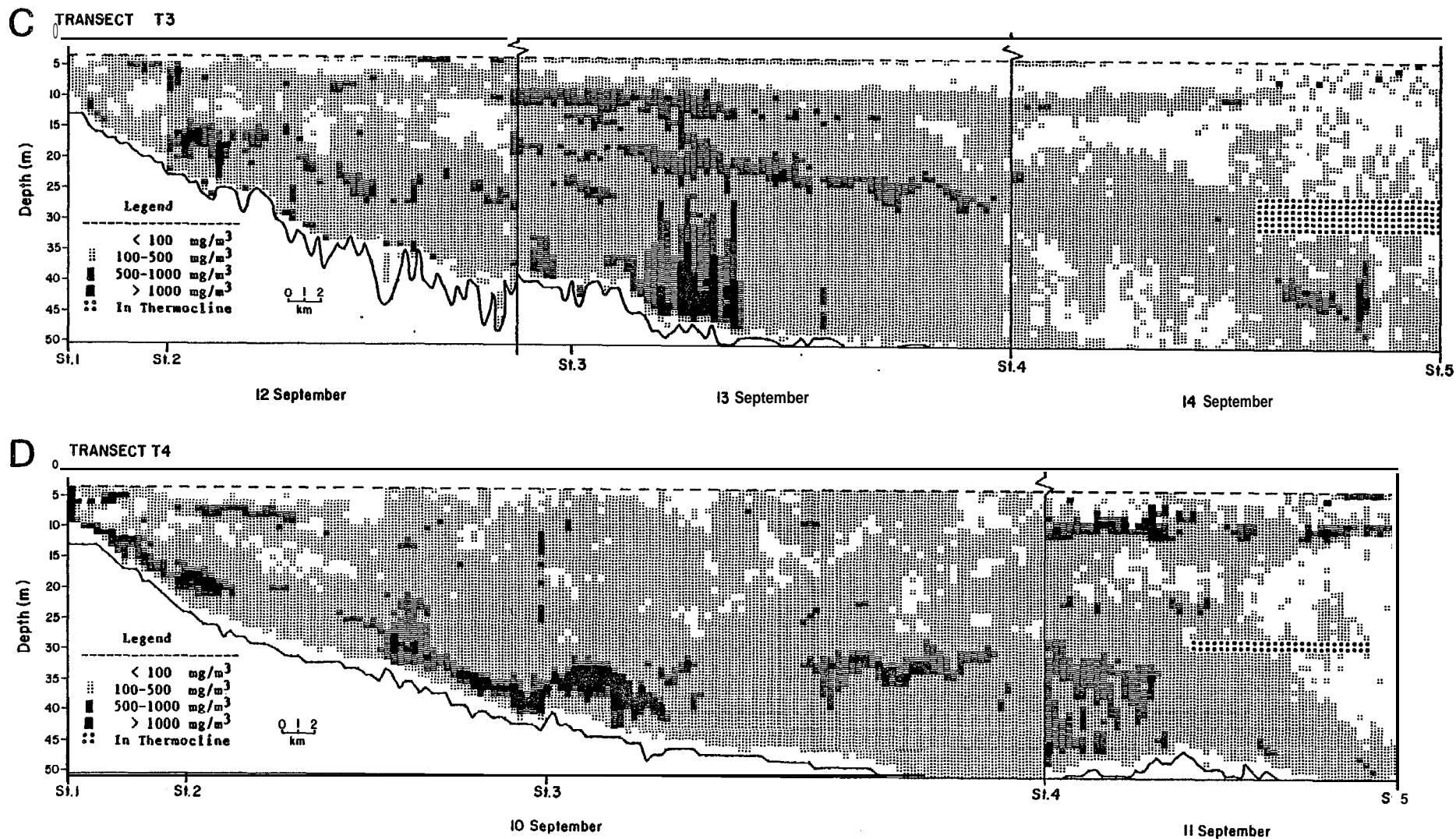


FIGURE 100. (Cent'd). Zooplankton patchiness along 1986 Transects T3 and T4.

to 7 km in length and 15 m in depth; Fig. 100A). Between patches the biomass usually was similar to that in the nearshore zone--100 to 500 mg/m<sup>3</sup>. However, near Station T1-4 estimated zooplankton biomass typically was higher. Near-surface waters contained little zooplankton (<100 mg/m<sup>3</sup>; Fig. 100A).

Over the outer shelf, between Stations T1-4 and T1-5, physical gradients associated with the Bering Sea Water prevented the collection of meaningful hydroacoustic data from about 20 to 35 m depth. Above these depths the estimated zooplankton biomasses were generally very low (<100 mg/m<sup>3</sup>). Below them at 35-45 m depth there appeared to be an extensive zooplankton patch about 6 km in length and 10 m in depth, with a density >1000 mg/m<sup>3</sup> (Fig. 100A). However, net sampling at these depths revealed low biomasses (range 44 to 85 mg/m<sup>3</sup>). This suggested that either the zooplankton were not effectively captured by the nets, or that there was also interference from physical gradients at these depths, or some combination of the two.

Along Transect T2, hydroacoustic data are available only for the nearshore and inner shelf regions. In these waters, zooplankton patches with density >1000 mg/m<sup>3</sup> were scattered throughout much of the water column, but were more abundant in the nearshore than in the inner shelf area (Fig. 100B). These patches were generally small in size (maximum length 1.0 km; depth 3 m). In nearshore waters, high density patches were most common near the bottom but sometimes were present at mid-water. In the inner shelf area, patches of zooplankton (>500 to 1000 mg/m<sup>3</sup>) were typically at mid-water 15-25 m deep (Fig. 100B). Waters near the surface all along the transect contained low estimated biomasses, and the thickness of this depauperate surface layer increased with increasing distance from shore (Fig. 100B).

Along Transect T3, zooplankton patches were scattered throughout the water column within the nearshore and inner shelf zones, but were much less common in the top 50 m of the outer shelf region (Fig. 100C). In the nearshore zone (Stations T3-1 to T3-3), only isolated patches of zooplankton with density >1000 mg/m<sup>3</sup> were found, primarily near the bottom around Station T3-2. The largest patch was approximately 1.0 km in length and 2 to 3 m in depth (Fig. 100C). Numerous small patches with density 500-1000 mg/m<sup>3</sup> were evident in this zone; however, at most depths zooplankton biomass was 100-500 mg/m<sup>3</sup>. Estimated biomasses were low (<100 mg/m<sup>3</sup>) in near surface waters (4 to 7 m depth) across the whole nearshore zone (Fig. 100C).

- Over the inner shelf between Stations T3-3 and T3-4, estimated zooplankton biomasses were higher than anywhere else on the transect (Fig. 100C). Offshore from Station T3-3, patches of zooplankton with biomass 500 mg/m<sup>3</sup> or greater occurred almost continuously through the water column, and >1000 mg/m<sup>3</sup> were found near the bottom (Fig. 100C). Some patches were quite extensive. For example, an almost continuous layer started just shoreward of Station T3-3 between 16 and 20 m depth, and continued for approximately 17 km seaward. There was a shorter (4.5 km) but much thicker (about 15 m) patch near the bottom seaward of Station T3-3. As in the nearshore area, estimated biomasses were low (<100 mg/m<sup>3</sup>) in the near surface waters (4 to 7 m depth).

Over the outer shelf, between Stations T3-4 and T3-5, there were few zooplankton patches; the only noteworthy case was a relatively small patch between 40 and 45 m depth near the end of the transect (Fig. 100C). Although

no net tows were taken at these depths, the possibility exists that the patch was partially an artifact of the Bering Sea Water. At most depths the estimated biomasses were 100-500  $\text{mg}/\text{m}^3$ . Biomasses  $<100 \text{ mg}/\text{m}^3$  were also common, particularly in the top 25 m (Fig. 100C).

Along Transect T4, zooplankton patches occurred mainly near the bottom in the nearshore and inner shelf zones, and higher in the water column in the middle and outer shelf region (Fig. 100D). In the nearshore area between Stations T4-1 and T4-3, zooplankton patches with estimated biomass  $>1000 \text{ mg}/\text{m}^3$  were generally near the bottom and small, about 1 to 2 km in length and 1 to 2 m thick. The one exception was a large patch (approximately 7 km by 1-5 m) near the bottom near Station T4-3 (Fig. 100D). At most depths, estimated biomasses between patches were 100-500  $\text{mg}/\text{m}^3$ . However, in near surface waters (4 to 7 m depth) biomasses were lower (Fig. 100D).

Over the inner shelf between Stations T4-3 and T4-4, zooplankton patches of  $>1000 \text{ mg}/\text{m}^3$  were evident near the bottom around Station T4-3 and at mid-water (depths 32-34 m) seaward of this station (Fig. 100D). Outside these patches, estimated zooplankton biomasses at most depths were 100-500  $\text{mg}/\text{m}^3$ , even in near surface waters.

Over the outer shelf between Stations T4-4 and T4-5, the densest zooplankton layers ( $>1000 \text{ mg}/\text{m}^3$ ) were in the upper portion of the water column (but below the surface layer) at depths from 6-11 m (Fig. 100D). These patches were relatively small, about 1.0 km long by 1-5 m deep (Fig. 100C). In addition, just seaward of Station T4-4 there was a relatively large zooplankton patch of medium density (500 to  $1000 \text{ mg}/\text{m}^3$ ) at mid-water. At most other depths zooplankton biomass was 100-500  $\text{mg}/\text{m}^3$ . However, in near surface waters (4 to 7 m deep) biomasses were lower (Fig. 100D).

Summary, 1985-86: With the exception of 1985 Transect 2 and 1986 Transect T1, zooplankton patches were more abundant in the nearshore and inner shelf water masses than over the outer shelf. The apparent exception for 1986 Transect T1 may have been an artifact of hydroacoustic return from physical gradients. In 1986, zooplankton patches were generally smaller in both length and depth than in 1985. In 1985, the highest biomasses were generally just below the pycnocline (6 to 10 m depth). In contrast, during 1986 the highest biomasses were usually deeper in the water column, typically just above the bottom in nearshore and inner shelf waters, and at mid-water in the middle and outer shelf regions. In waters near the surface (4 to 7 m depths), zooplankton biomass was typically low in both years.

In both years of the study, only a fraction of the water along the broad-scale transects contained a high biomass of zooplankton. Based on the hydroacoustic data shown in Figures 99 and 100, we determined the frequencies of various biomasses, with the units of observation being segments of water with lengths about 250 m in 1985 and 365 m in 1986 (2-rein of boat transect), and thicknesses 2 m in 1985 and 1 m in 1986. Of these segments, 90% contained an estimated biomass  $<500 \text{ mg}/\text{m}^3$  in 1985, and 88% did so in 1986. In each year, only 2% of the segments contained an estimated biomass  $>1000 \text{ mg}/\text{m}^3$ , and only 0.3-0.5% contained  $>2000 \text{ mg}/\text{m}^3$  (Table 15). The overall averages of the estimated zooplankton biomasses along the broad-scale transects were similar in the two years of study, 249 and 270  $\text{mg}/\text{m}^3$  for 1985 and 1986 respectively.



**Table 15.** Frequency of occurrence of various **zooplankton biomasses** in small segments of **the** broad-scale transects. Estimated from 200 kHz **hydroacoustic** data from the top 50 m of **the** water column, excluding **the** same situations **as** were excluded from Fig. 99 and 100. Segments were about 250 m long x 2 m thick in 1985, and 365 m long x 1 m thick in 1986.

Range of Biomass (mg/m <sup>3</sup> )	1986 Transects T1 to T4		1985 Transects 1 and 2	
	No.	of Seg. %	No.	of Seg. % "
0-249	13969	59.4	3617	68.7
250-499	6630	<b>28.2</b>	<b>1119</b>	21.3
500-749	<b>1788</b>	<b>7.6</b>	322	<b>6.1</b>
750-999	600	<b>2.6</b>	<b>100</b>	1.9
1000-1249	<b>246</b>	<b>1.1</b>	27	<b>0.5</b>
1250-1499	<b>144</b>	<b>0.6</b>	24-	<b>0.5</b>
1500-1749	84	0.4	<b>10</b>	<b>0.2</b>
1750-1999	30	<b>0.1</b>	<b>17</b>	0.3
2000-2249	<b>7</b>	<b>0.0</b>	<b>12</b>	0.2
2250-2499	<b>1</b>	<b>0.0</b>	<b>5</b>	" <b>0.1</b>
2500-2749	<b>1</b>	0*0	8	<b>0.2</b>
<b>2750-2999</b>	0	0 . 0	2	0.0
3000-3249	<b>1</b>	0.0	0	0.0
3250-3499	<b>1</b>	<b>0.0</b>	0	0.0
3500-3749	<b>1</b>	<b>0.0</b>	0	<b>0.0</b>
3750-3999	0	.0.0	0	<b>0.0</b>
<b>Total</b>	<b>23503</b>	<b>100.0</b>	<b>5263</b>	<b>100.0</b>

**Biomass vs. Water Depth and Sampling Depth.**--Table 16 shows the average **zooplankton** biomass for each part of **the** continental **shelf, depth** and **transect**, based on **the** same **hydroacoustic** data. The **overall** estimates were similar for corresponding zones in the two years, In September 1985, the **biomasses** estimated from **hydroacoustic** surveys decreased with increasing **distance** from **shore**, consistent with the results of **the** **net** sampling. In September 1986, estimated biomasses did not show this trend as clearly (Table 16). This was due in **part** to the high estimated **biomasses** at **the** north ends of Transects T1 and T3, where some estimates may have been artifacts caused by the **Bering Sea Water**.

**Depth** related differences in the **estimated zooplankton** biomass were evident between **the two years** of the study. The highest **estimates** were between 11 and 25 m depths in' September 1985, but typically were between 26 and 50 m in September 1986 (Table 16). For **almost all** categories, the average was <400 mg/m<sup>3</sup>.

Table 16. Estimated zooplankton biomass for **small** segments of the broad-scale transects, subdivided **by** zone, transect and depth in the water column. Estimated from 200 kHz hydroacoustic data from the top 50 m of the water column, excluding the same situations as were excluded from Figures 99 and 100. Segments were about 250 m long x 2 m thick in 1985, and 365 m long x 1 m thick in 1986. In each case,  $n \geq 10$ .

	Nearshore	Inner Shelf	Outer Shelf	Al 1
	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
<b>1985</b>				
Depth <10 m	390 * 444	133 * 74		308 $\pm$ 387
11-25 m	475 $\pm$ 539	344 $\pm$ 345	276 * 354	323 $\pm$ 372
26-50 m	<b>-a</b>	184 * 171	170 $\bullet$ 143	175 * 155
Transect 1	539 $\pm$ 492	285 $\pm$ 345	167 $\pm$ <b>160</b>	232 $\pm$ 286
2	344 $\pm$ 535	254 $\pm$ 237	266 $\pm$ 326	263 $\pm$ 299
<b>All</b>	455 * <b>519</b>	266 $\pm$ 286	214 $\pm$ 258	249 * 293
<b>1986</b>				
Depth <10 m	203 * 216	<b>134 * 146</b>	163 $\pm$ 258	<b>168 <math>\pm</math> 207</b>
11-25 m	318 * 235	284 $\pm$ <b>178</b>	132 * 137	260 * 207
26-50 m	304 * 255	331 $\pm$ 254	328 $\pm$ 342	325 $\pm$ 284
Transect <b>1</b>	263 $\pm$ <b>181</b>	<b>313 * 211</b>	442 $\pm$ 534	321 * 308
2	325 * 274	<b>216 <math>\pm</math> 147</b>		266 $\pm$ 222
3	<b>261 <math>\pm</math> 198</b>	330 $\pm$ 235	149 $\pm$ 131	248 $\pm$ 209
4	294 $\pm$ 291	<b>261 * 250</b>	243 $\pm$ 225	263 $\pm$ 254
<b>Al 1</b>	285 $\pm$ <b>241</b>	283 $\pm$ 226	232 $\pm$ 288	270 $\pm$ 249

<sup>a</sup> Values not shown when number of segments <10.

These findings have important implications for bowhead whales. In both years, **zooplankton** biomass in the top few meters of the water was very low. Thus, **bowheads** would not be expected to feed at the surface in our study area and study periods. The majority of the **zooplankton** was at depths >5 m, but in the upper 50 m of the water column. This was true even over waters as much as 200 m deep. Thus, concentrations of **zooplankton** would be easily accessible to feeding whales.

Most of the water, even at depths <50 m, contained relatively low biomasses of zooplankton (Table 15). At many places there were no major concentrations of **zooplankton** at any depth (Fig. 99, 100). Bowheads would be

expected to concentrate their feeding at the relatively small number of locations and depths in the water column where zooplankton was most abundant. The proportion of the study area where food was sufficiently abundant for energetically profitable feeding is evaluated in the 'Integration' section after energetic requirements of bowheads have been discussed.

### Zooplankton Near Fronts

Oceanographic fronts were found in the study area during September of 1985 and 1986 (see 'Water Masses' section, p. 114-124). We examined the physical and biological data to determine if zooplankton tended to accumulate near these features (Table 17).

Chlorophyll a concentrations at the surface were extremely low in 1986 and were almost undetectable. Changes in these low concentrations along the transects have little meaning. Average concentrations were about five times higher in 1985 ( $0.5 \text{ mg/m}^3$  in 1985 vs.  $0.1 \text{ mg/m}^3$  in 1986).

In 1985 the echosounder data provided weak evidence that zooplankton was more concentrated within frontal areas than outside frontal areas. Mean zooplankton concentrations within and outside fronts were not different. However, considering the maximum biomass at any depth, the mean of this variable was 50% higher within fronts than outside fronts (Table 17). Although variability was high, the difference was marginally significant ( $t = 1.82$ ,  $df = 46$ , 1-sided  $p < 0.05$ ). Griffiths et al. (1986, p. 138-142) provide more details.

In 1986 there was no obvious relationship between the distribution of oceanographic properties and the broad-scale distribution of zooplankton biomass (Fig. 'I01-105, Table 17). Mean and maximum biomasses were similar within and outside frontal areas.

The locations of the fronts considered here were determined from surface water properties. Frontal features evident at the surface were not always indicative of a corresponding subsurface front. This lack of correspondence between surface and subsurface fronts may have been responsible for the apparent lack of concentration of zooplankton near surface fronts. Also, the horizontal resolution of the data may have been inadequate to detect some concentrations.

### Caloric Content of the Zooplankton

The summer growing season for arctic phytoplankton is short. During this period the herbivorous zooplankters must store enough energy to enable them to survive the long period of food scarcity in winter. Zooplankters store energy in the form of lipids (Raymont 1983). In arctic zooplankters, lipid content and thus caloric content is lowest at the end of winter and highest at the end of summer (Lee 1974). Lowry and Frost (1984) suggested that feeding in the Eastern Alaskan Beaufort Sea and elsewhere during late summer and early autumn may be especially important to bowhead whales because of the high energy content of zooplankton at that time of year. No data on energy content of zooplankton had been acquired in our study area before 1985.

Table 17. Oceanographic parameters and zooplankton within and away from fronts, September 1985 and 1986. Based on measurements within 15 minute (temperatures salinity, chlorophyll, 1985 zooplankton) and 2 minute (1986 zooplankton) segments of echosounder transects. Each segment was categorized as being within or away from the fronts described in 'Water Masses' and shown on Figures 63 and 64 (p. 118-119). Zooplankton biomasses were estimated by 200 kHz echosounder.

	1986, Transects T1-T4		1985, Transects 1 + 2	
	Within Fronts	Away from Fronts	Within Fronts	Away from Fronts
	Mean $\pm$ s.d. n	Mean $\pm$ s.d. n	Mean $\pm$ s.d. n	Mean $\pm$ s.d. n
Surface Temperature ( $^{\circ}\text{C}$ )	2.7 $\pm$ 1.0 (57)	2.0 $\pm$ 1.1 (46)	1.3 $\pm$ 0.7 (23)	1.4 $\pm$ 0.8 (23)
Surface Salinity (psu)	25.9 $\pm$ 1.1 (57)	25.8 $\pm$ 0.5 (46)	27.0 $\pm$ 1.8 (23)	26.5 $\pm$ 2.4 (32)
Chlorophyll <u>a</u> <sup>a</sup>	0.09 $\pm$ 0.04 (56)	0.06 $\pm$ 0.02 (46)	0.58 $\pm$ 0.36 (23)	0.46 $\pm$ 0.36 (32)
Mean estimated zooplankton biomass ( $\text{mg}/\text{m}^3$ ; total water column) <sup>b</sup>	294 $\pm$ 111 (304)	266 $\pm$ 122 (344)	270 $\pm$ 159 (21)	279 $\pm$ 178 (27)
Maximum estimated zooplankton biomass at any depth ( $\text{mg}/\text{m}^3$ ) <sup>b</sup>	901 $\pm$ 446 (304)	803 $\pm$ 412 (344)	1050 $\pm$ 777 (21)	666 $\pm$ 683 (27)

<sup>a</sup> 1986, relative units (0.1 unit is roughly 0.1  $\text{mg}/\text{m}^3$ ); 1985,  $\text{mg}/\text{m}^3$

<sup>b</sup> 1986, between depths of 4 and 50 m; 1985, below the pycnocline to 50 m.

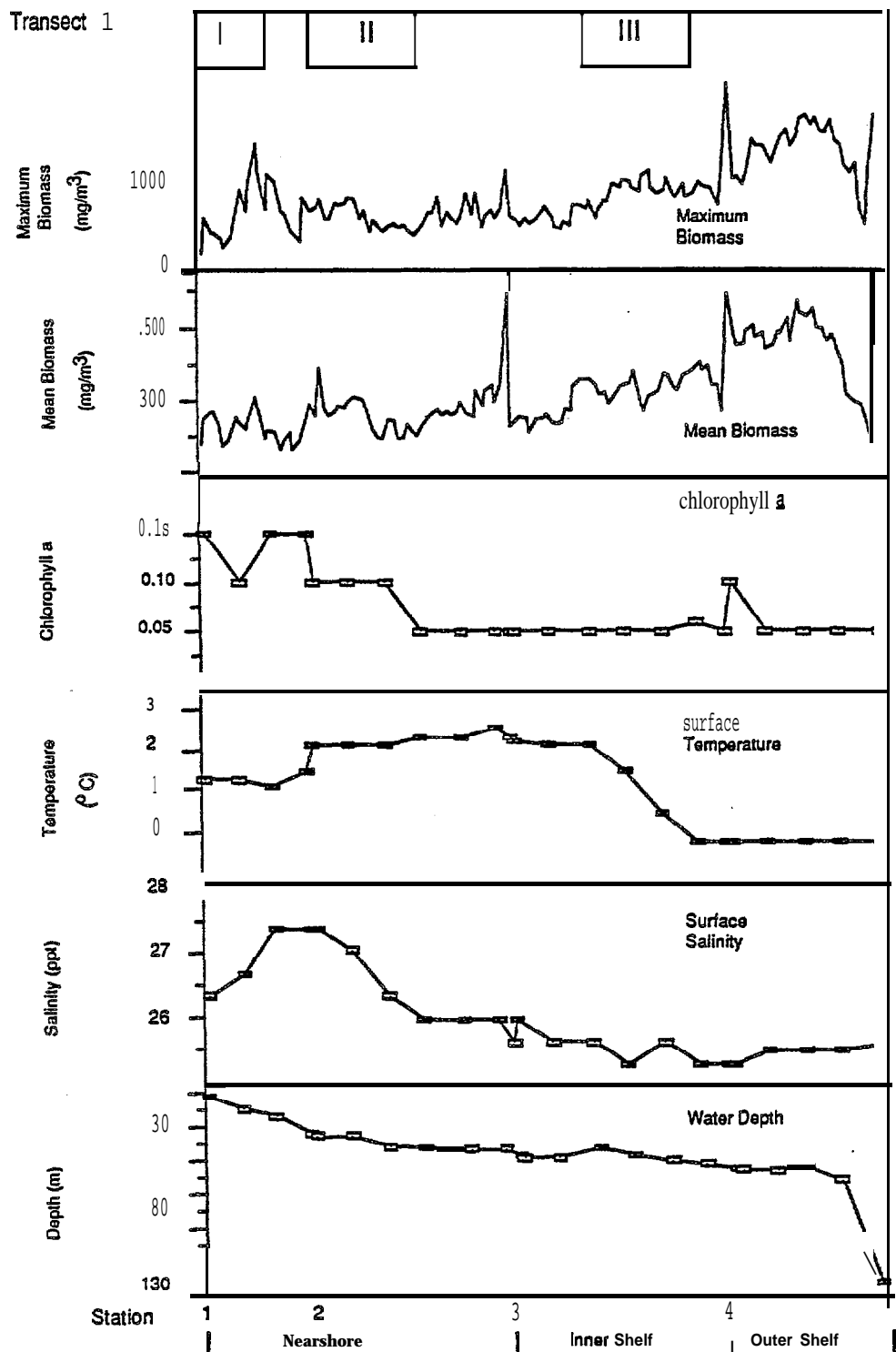


FIGURE 101. Mean and maximum zooplankton biomass in the water column vs. chlorophyll, temperature and salinity at the surface, 'Transect 1, September 1986. Biomass was estimated from the 200 kHz echosounder data, considering depths from 4 to 50 m and not including the pycnocline. Maximum biomass is the maximum biomass at any depth. Biomass data are plotted for each 2 min (approx. 365 m) segment. Chlorophyll, salinity and temperature were recorded at 15 min intervals. Chlorophyll data are expressed as relative fluorometer units. Also shown are the locations of the fronts described in the 'Water Masses' section (Fig. 63, 67).

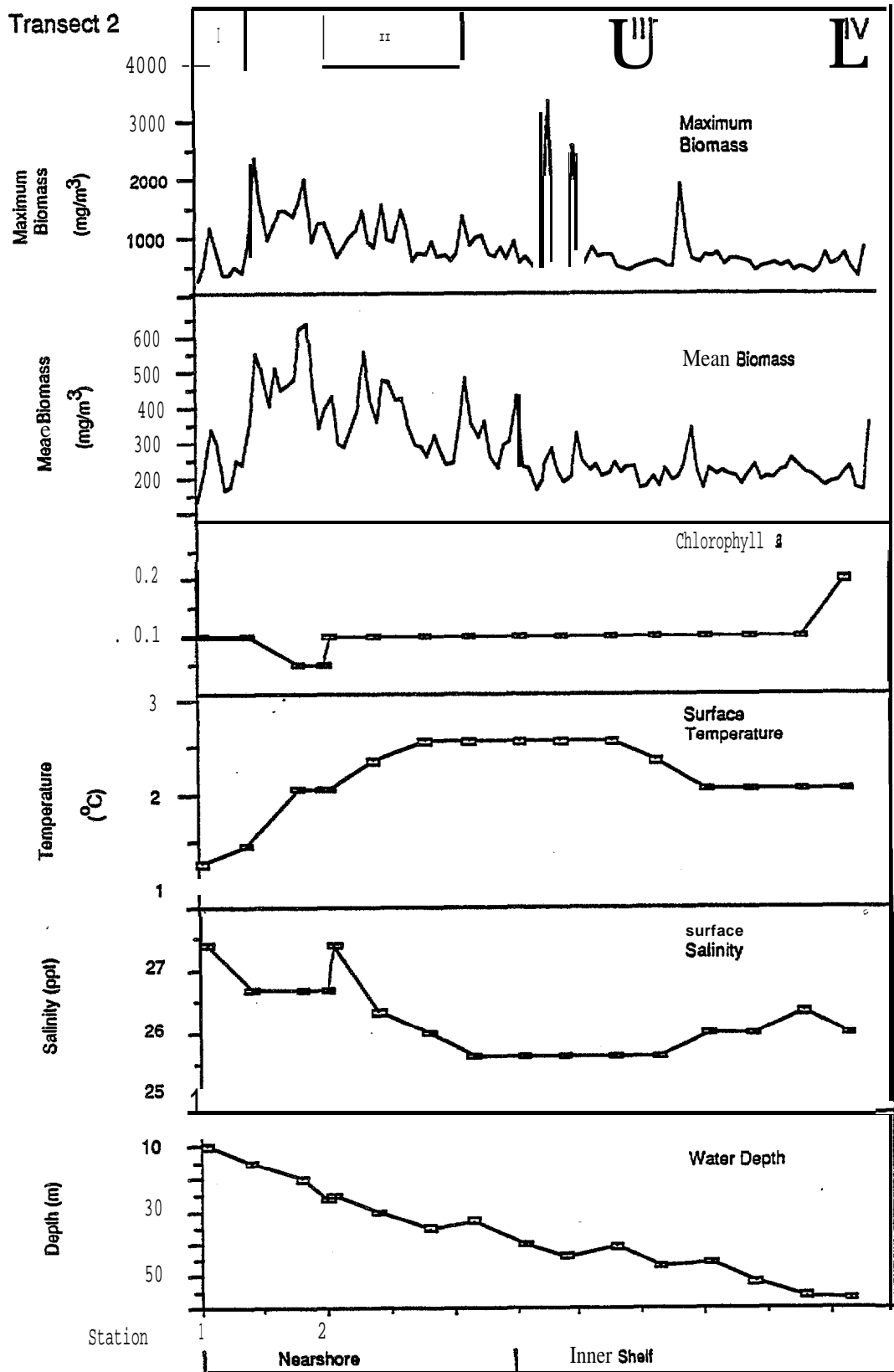


FIGURE 102. Mean and maximum zooplankton biomass in the water column vs. chlorophyll, temperature and salinity at the surface, Transect 2, September 1986. Data are plotted as in Figure 101. Fronts I-IV are described in the 'Water Masses' section (Fig. 63, 67).

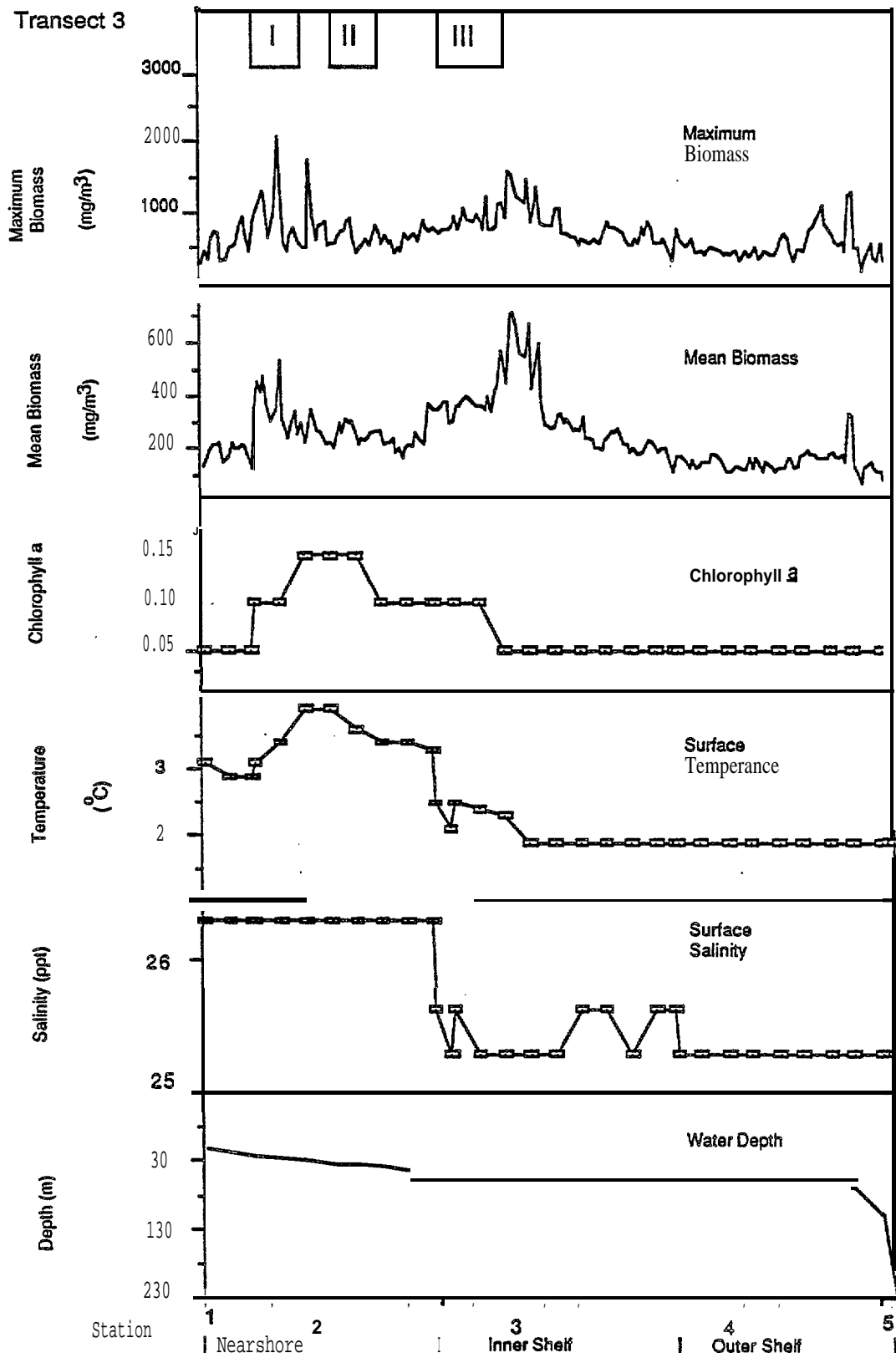


FIGURE 103. Mean and maximum zooplankton biomass in the water column vs. chlorophyll, temperature and salinity at the surface, Transect 3, September 1986. Data are plotted as in Figure 101. Fronts I-III are described in the 'Water Masses' section (Fig. 64, 68).

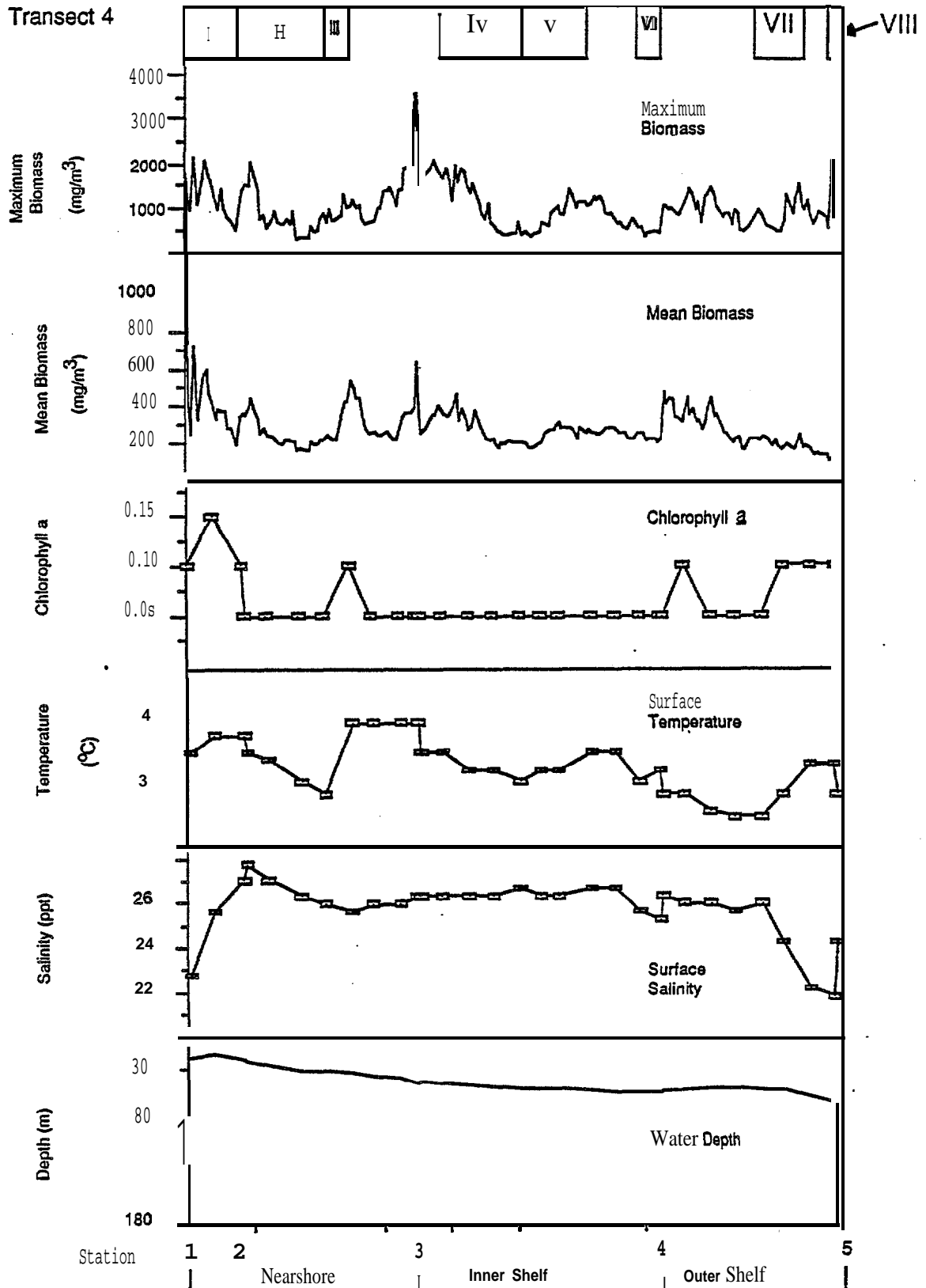


FIGURE 104. Mean and maximum zooplankton biomass in the water column vs. chlorophyll, temperature and salinity at the surface, Transect 4, September 1986. Data are plotted as in Figure 101. Fronts I-VIII are described in the 'Water Masses' section (Fig. 64, 68).



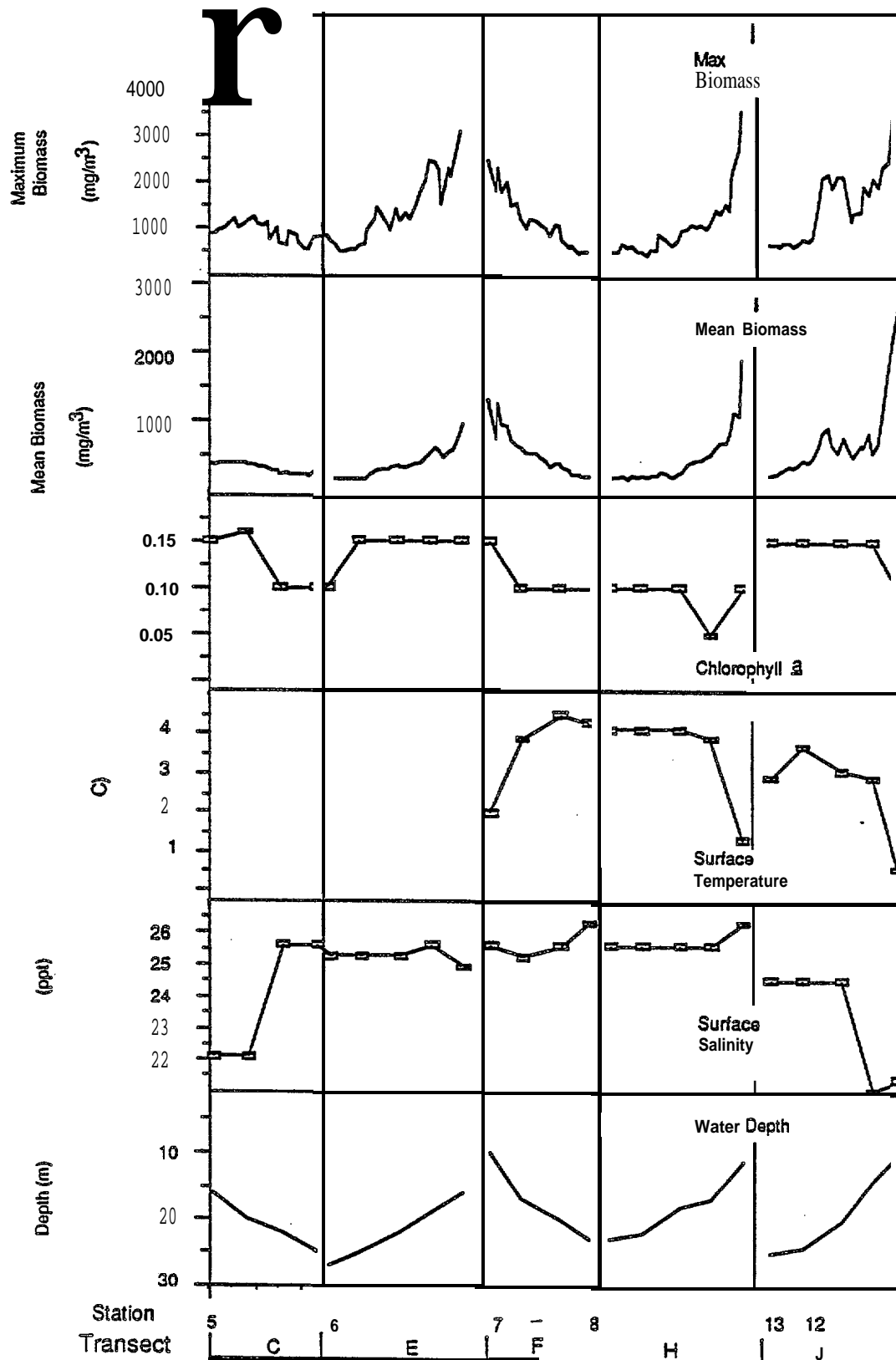


FIGURE 105. Mean and maximum zooplankton biomass in the water column vs. chlorophyll, temperature and salinity at the surface along nearshore transects C, E, F, H and J near whale feeding areas, September 1986. Data are plotted as in Figure 101.

In 1985, **copepods** had higher caloric **content** per **unit** dry weight than **did** any other taxon analyzed. Caloric content of the **copepods** was considerably **lower in** 1986 (6297 **cal/g**) than in 1985 (7368 **cal/g** for **large copepods**; 6635 **cal/g** for **small copepods**). The caloric content of copepods collected in October 1986 was much lower than in September (Table 18). Bradstreet et al. (1987) also found a **lower** caloric content in zooplankton samples from the Canadian Beaufort Sea in 1986 than in 1985. Conditions appear to have been more conducive for growth of copepods in 1985 than in 1986. Differences in September chlorophyll concentrations between the two years provide one clue as to the cause of differences in caloric content. In 1986, surface chlorophyll **a** concentrations were barely detectable and were at **least** 5 times lower than those recorded in 1985 (Table 17).

To assess **the** relative caloric content of various major taxa in the Eastern Alaskan Beaufort Sea, the data in Tables 18 and 19 were used to convert wet weight biomass to caloric content for each major group of organisms in each **sample** (Table 20). Copepods accounted for about 80% of wet weight, 85% of dry weight, and 89% of caloric content in both years. **Hydrozoans** and ctenophores accounted for 8-9% of the wet weight, but their energy content was low. **Euphausiids** were less common in the study area in 1986 than in 1985. Dry weight of **zooplankton** in **all** samples was 16.5% (1985) and 17.3% (1986) of wet weight. These values are comparable to those found by most other authors (Parsons et al. 1977; Ikeda and Motoda 1978).

Considering all horizontal and oblique tows, mean caloric content of zooplankton per cubic meter of water sampled was considerably higher in 1986 than in 1985 (Table 20). However, this difference was largely attributable to the many horizontal tows taken in **zooplankton** patches within **whale** feeding areas in 1986. Mean caloric **content/m<sup>3</sup>** for zooplankton taken in oblique tows **along** broad-scale transects was 225 **cal/m<sup>3</sup>** in 1985 and 179 **cal/m<sup>3</sup>** in 1986. The lower average in 1986 reflected the **lower** energy content of the zooplankton per gram in 1986.

The highest concentrations of caloric **content/m<sup>3</sup>** were found within **layers** of **zooplankton** where whales were observed to be feeding (Table 21). In these areas a mean of 2132 **cal/m<sup>3</sup>** was available to feeding bowhead whales. This **value** is 4 **times** higher than **values** recorded in nearby control areas and twice as high as the mean for **other** nearshore areas (570 and 1005 **cal/m<sup>3</sup>**, respectively; Table 21). The mean values for layers of **zooplankton** in the nearshore and inner shelf zones in 1985 in the absence of whales were only 511 and 667 **cal/m<sup>3</sup>** (Griffiths et al. 1986, p. 129). The caloric **content** of the **zooplankton** in terms of **cal/g** dry weight and **cal/g** wet weight were also highest in samples taken from the whale feeding stations (Table 21). Thus, not **only** was the biomass and caloric content of the zooplankton, on a 'per **m<sup>3</sup>**' basis, highest in the **whale** feeding areas, but the nutritional value of the **zooplankton** per unit weight was **also** higher there.

Table 18. Mean caloric content (cal/g dry weight) of copepods and other zooplankton taxa taken in the Alaskan Beaufort Sea in September 1985-86 and October 1986. Sample sizes are shown in parentheses.

Copepods	Mean s.d. . n	Other Taxa	Mean s.d. n
<u>September 1986</u>			
All Copepods	6297 ± 619 (47)		
Whale Feeding Stations	6391 ± 677 (10)	Amphipods <15 mm	5480 ± 63 (2)
Control Stations	5914 ± 151 (8)	Amphipods >15 mm	7117 ± 380 (6)
Nearshore (<20 m)	6219 ± 384 (15)	Hydrozoans	4867 ± 742 (8)
Inner shelf (20-50 m)	6636 ± 857 (8)	Fish larvae	5193 ± 56 (3)
Outer shelf (50-200 m)	6399 ± 872 (6)	Composite samples	4835 ± 588 (19)
<u>October 1986</u>			
Au Copepods	4718 ± 351 (13)	Euphausiids 10-15 mm	4332 ± 17 (2)
Outer shelf (50-200 m)	4905 ± 182 (3)	17-25 m	5079 ± 243 (16)
Off the shelf (>1500 m)	4662 ± 377 (10)	25-30 m	5342 ± 244 (7)
		All	5093 ± 344 (25)
		Ctenophores	2050 ± 688 (7)
		Chaetognaths	4205 ± 127 (4)
		Scyphozoa	802 ± 218 (6)
		Cod Larvae	3980 ± 90 (5)
<u>September 1985</u>			
Copepods <1.8 mm (all)	6635 ± 483 (10)	Hyperiid amphipods	6437 ± 881 (9)
Nearshore (<20 m)	6552 ± 469 (5)	Gammarid amphipods	5502 ± - (1)
Inner shelf (20-50 m)	7087 ± 240 (3)	Mysids	5126 ± 612 (3)
Outer shelf (50-200 m)	6161 ± 69 (2)	Pteropods	4533 ± 23 (2)
Copepods >1.8 mm (all)	7368 ± 406 (17)	Decapod larvae	4214 ± 399 (3)
Nearshore (<20 m)	7353 ± 246 (2)	Cod larvae	4838 ± 437 (5)
Inner shelf (20-50 m)	7313 ± 653 (6)	Liparid larvae	4668 ± - (1)
Outer shelf (50-200 m)	7407 ± 228 (9)	Composite samples	7191 ± 879 (3)

Table 19. Mean dry **weight** expressed as a percentage of wet weight for various zooplankton taxa taken in plankton tows in the Eastern Alaskan Beaufort Sea, September 1986.

	Mean $\pm$ s.d.		n
<b>Copepods</b>	<b>18.3</b>	1.1	5
Euphausiids	<b>19.8</b>	<b>1.6</b>	5
<b>Mysids</b>	<b>20.1</b>	<b>1.2</b>	5
<b>Hyperiid</b>	<b>16.6</b>	<b>2.5</b>	5
<b>Chaetognaths</b>	<b>6.6</b>	0.6	5
<b>Hydrozoans</b>	<b>11.4</b>	2.2	5
<b>Ctenophores</b>	9.8	<b>1.8</b>	5
Decapod larvae	13.4	<b>1.3</b>	5
Fish larvae	16.8	<b>1.4</b>	5

Table 20. Wet weight, dry weight and caloric content of major groups of zooplankton collected in the Eastern Alaskan Beaufort Sea, September 1985-86. Mean **values** are expressed as percentages of the mean total of all samples.

Taxa	% Wet Weight		% Dry Weight		% Caloric Content	
	1985	1986	1985	1986	1985	1986
Copepods	78.0	80.8	85.1	85.3	89.8	89.2
<b>Pteropods</b>	<b>1.4</b>	<b>1.1</b>	<b>1.2</b>	<b>1.0</b>	0.8	<b>0.8</b>
Mysids	<b>1.7</b>	2.4	<b>1.8</b>	2.7	<b>1.3</b>	2.3
<b>Euphausiids</b>	2.6	0.2	<b>3.4</b>	0.2	2.5	0.2
<b>Amphipods</b>	2.2	<b>1.2</b>	2.6	<b>1.2</b>	2.4	<b>1.3</b>
Fish larvae	<b>1.5</b>	<b>1.5</b>	<b>1.3</b>	1.4	<b>0.9</b>	1.2
Gelatinous Zooplankton <sup>a</sup>	8.0	<b>9.1</b>	2.0	5.6	0.5	3.1
<b>Chaetognaths</b>	2.6	0.9	1.5	0.4	<b>1.1</b>	<b>0.2</b>
Other taxa	2.0	2.8	1.1	2.2	0.7	<b>1.6</b>
Mean of all samples (/m <sup>3</sup> )	230	393 <sup>b</sup>	mg 38	68 <sup>b</sup> mg	259	410 <sup>b</sup> Cal
s.d. (/m <sup>3</sup> )	236	<b>710</b>	41	129	290	807
sample size (tows)	43	119	43	119	43	119

<sup>a</sup> Hydrozoans and ctenophores.

<sup>b</sup> Mean for 1986 exceeds that for 1985 because 1986 sampling included whale feeding areas.

Table 21. Mean ( $\pm$  s.d. ) wet weight, dry weight and caloric content of zooplankton collected in various situations in 1986. Caloric content per unit dry weight and wet weight is also shown. For similar 1985 data, see Griffiths et al. (1986, p. 129).

	Wet Weight (mg/m <sup>3</sup> )	Dry Weight (mg/m <sup>3</sup> )	cal/m <sup>3</sup>	Dry wt. as percent of wet wt.	Dry Weight (cal/g)	Wet Weight (cal/g)	Sample Size <sup>a</sup>
<b>A. Top 50 m of Water Column</b>							
<b>Whale Feeding Areas, Sept '86</b>							
Whale Stns	586 $\pm$ 476	105 $\pm$ 87	643 $\pm$ 555	17 $\pm$ 2	5726 $\pm$ 611	977 $\pm$ 209	6
Control Stns	86 65	13 10	72 56	15 1	5417 640	842 160	5
<b>Broad-Scale Transects, Sept '86</b>							
Nearshore	296 389	52 71	317 449	17 2	5630 716	919 233	8
Inner Shelf	170 128	28 22	162 141	16 1	5568 687	887 178	3
Outer Shelf	43 21	6 3	29 18	14 2	5052 625	696 170	7
All Transects	177 280	30 51	179 322	15 2	5395 698	827 220	18
<b>October 1986</b>							
Main Study Area	112 108	14 12	6448	13 2	5034 810	677 188	15
All AK Beaufort	175 244	22 29	96 111	14 2	4893 770	677 189	25
<b>B. Surface Tows, Sept '86</b>							
<b>Whale Feeding Areas</b>							
Whale Stns	20 $\pm$ 28	3 $\pm$ 5	20 $\pm$ 31	15 $\pm$ 2	5265 $\pm$ 653	806 $\pm$ 183	6
Control Stns	9 12	1 2	6 6	15 2	502 921	765 260	5
<b>Broad-Scale Transects</b>							
Nearshore	70 73	13 13	78 84	17 2	5837 669	975 242	3
Inner Shelf	13 19	2 2	8 10	15 2	5162 795	775 210	3
Outer Shelf	2 3	0 0	2 2	16 1	5657 380	912 89	4
All Transects	26 47	4 9	26 53	16 2	5563 609	890 180	10

Continued . . .

Table 21. Concluded.

	Wet Weight (mg/m <sup>3</sup> )	Dry Weight (mg/m <sup>3</sup> )	cal/m <sup>3</sup>	Dry wt. as percent of wet wt.	Dry Weight (cal/g)	Wet Weight (cal/g)	Sample Size <sup>a</sup>
<b>C. Horizontal Tows Below Surface, Sept '86- Within Zooplankton Layers<sup>b</sup></b>							
<b>Whale Feeding Areas</b>							
Whale Stns	1899 ± 1276	344 ± 233	2132 ± 1450	18 ± 1	6083 ± 358	1079 ± 128	10
Control Stns	568 594	96 106	570 650	15 2	5330 838	830 239	5
<b>Broad-Scale Transects</b>							
Nearshore	923 913	163 167	1005 1059	17 1	5842 530	993 156	9
Inner Shelf	559 494	96 90	573 577	16 1	5671 659	937 186	5
Outer Shelf	246 272	36 44	188 272	13 2	4684 925	629 243	12
All Transects	541 658	92 120	545 763	15 2	5275 922	814 265	26
<b>D. Horizontal Tows Below Surface, Sept '86- Outside Zooplankton Layers<sup>b</sup></b>							
<b>Whale Feeding Areas</b>							
Whale Stns	66 ± 29	10 ± 5	49* 31	14 ± 2	4855 ± 812	693 ± 199	4
Control Stns	166 83	25 14	126 87	14 1	4872 620	710 163	5
<b>Broad-Scale Transects</b>							
Nearshore	108 60	17 11	94 69	15 2	5191 721	798 198	9
Inner Shelf	49 10	7 1	3 4 7	15 1	4821 122	699 11	2
Outer Shelf	71 44	8 5	34 16	13 2	4294 776	549 187	3
All Transects	92 56	14 10	73 62	15 2	4946 745	731' 201	14

<sup>a</sup> Number of bongo tows<sup>b</sup> Horizontal tows below the surface were categorized as being made within or outside layers of zooplankton detectable by the echosounders.

### Discussion

The official study area represents the westernmost portion of the summer feeding range for bowhead whales. During the arctic summer, July-August, few bowheads have been observed in the region. By September, many bowheads have begun a gradual westward movement from the Canadian Beaufort Sea; these whales are still feeding much of the time. Feeding late in the season may be especially important since it may be the last feeding period for several months and the energy content of zooplankton is high at this time of year. In relation to the Alaskan Beaufort Sea as a whole, the study area appears to be a favored region since feeding bowheads have been identified there each year since 1979 (Ljungblad et al. 1986a; this study). Feeding in this region seems to be more frequent and prolonged than in areas farther west.

### Group and Species Composition

The group and species composition of the zooplankton communities are similar in different areas of the Beaufort Sea and in various other arctic regions. Typically, copepods (particularly Calanus) contribute most of the numbers and biomass, although their vertical movements can cause seasonal variations in their relative abundance near the surface. Hopkins (1969) found that copepods were the major contributors in the Arctic Surface, Atlantic and Arctic Deep water layers, representing 83, 85 and 89% of the biomass, respectively. Similarly in the eastern high arctic, copepods constituted 79% of the total zooplankton biomass in the upper 150 m of Lancaster Sound and 84% in the upper 150 m of northwest Baffin Bay (Sekerak et al. 1976a, 1979; Buchanan and Sekerak 1982).

Copepods dominate the zooplankton in the Beaufort Sea. Grainger and Grohe (1975) found that copepods contributed over 90% of the individuals in the Mackenzie Delta and Herschel Island area; Griffiths and Buchanan (1982) found that copepods represented 72% of the zooplankton biomass off the outer Mackenzie Delta in 1981. Homer (1979, 1981), in a study that included portions of our study area, reported that copepods contributed an average of 63% (range 3-91%) of the individuals in the zooplankton community. Bradstreet and Fissel (1986) found that copepods constituted 86% of the biomass and 99% of the individual zooplankters just to the east of our study area, along the Yukon coast, in 1985. In the present study, copepods represented 87 and 98% of the individual zooplankters collected during September of 1985 and 1986, respectively. They represented 78 and 81% of the wet weight zooplankton biomass in those two periods. In October of 1986, copepods accounted for 85% of the individuals but only 24% of the biomass in the upper 50 m of the water column at mid-shelf and deeper stations in our main study area, probably because the downward migration had begun.

Other groups that occasionally contribute significantly to the zooplankton community include hydrozoans, ctenophores, amphipods, mysids, euphausiids, chaetognaths, pteropods, decapods, fish larvae and larvaceans (Hopkins 1969; Sekerak et al. 1976a, 1979; Homer 1979, 1981; Griffiths and Buchanan 1982; Bradstreet and Fissel 1986; this study). Any of the above groups may be locally abundant and at times overshadow the importance of copepods. This type of variable local abundance has been reflected in the stomach contents of bowhead whales. For example, several groups of

zooplankters (e.g., small and large copepods, euphausiids, mysids, hyperiid and gammarid amphipods) have contributed to the stomach contents of bowheads taken near Kaktovik in autumn. At Barrow, euphausiids contributed significantly to the diets of two whales taken in autumn and four whales taken in spring (Lowry and Frost 1984; Lowry et al. 1987).

In September of 1985-86 and October of 1986, the group structure and species composition of the zooplankton community were similar to those of arctic regions in general, and to other results from the Beaufort Sea. However, the dominant species differed somewhat between years. For example, in September 1985, five species of copepods contributed significantly to the zooplankton biomass in the area--Calanus hyperboreus, C. glacialis, Limnocalanus macrurus, Derjuginia tolli and Euchaeta glacialis--while in September of 1986 only the first three were major contributors. In the mid-shelf and deeper waters sampled during October 1986, a single species, C. glacialis, was the dominant copepod. In other years, different copepod species have been found to be dominant in portions of our study area. Homer (1981) found Pseudocalanus spp. to be very abundant in this region in 1977-78, whereas it was only a minor contributor to the zooplankton biomass during 1985-86. All these species have been reported commonly in the Beaufort Sea, and most have been found in other arctic regions.

Each of the other major zooplankton groups was "generally represented by one or a few species, each of which has been reported commonly from the Beaufort Sea. For example, hydrozoans were dominated by Aglantha digitale and Halitholus cirratus, ctenophores by Mertensia ovum, chaetognaths by Sagitta elegans, mysids by Mysis litoralis, euphausiids by Thysanoessa raschii, amphipods by Parathemisto libellula and fish larvae by Boreogadus saida. Thus, although individual groups and/or species of zooplankton change in dominance among years and locations, the zooplankton community in the Eastern Alaskan Beaufort Sea is not noticeably different from communities elsewhere along the Beaufort Sea coast and in other arctic regions.

#### Density of Zooplankton

Comparisons of zooplankton standing crop within different areas are confounded by patchiness in the abundance and distribution of zooplankton, the wide variety of net and mesh sizes used in various studies, and the fact that most authors report their results in terms of numbers (densities) rather than biomasses. Despite these limitations, some general patterns in zooplankton density in the Beaufort Sea have emerged.

Zooplankton densities are higher over the continental shelf than over deeper offshore waters. Hopkins (1969) sampled zooplankton from ice islands T-3 and Arlis II in the Arctic Ocean north of the Beaufort Sea. He found the Arctic Surface Layer (depths 0-200 m) to be more 'productive' (averages of 56 indiv/m<sup>3</sup>; 0.62 mg dry wt/m<sup>3</sup>) than either the Atlantic Layer (depths 200-900 m; 13 indiv/m<sup>3</sup>; 0.14 mg dry wt/m<sup>3</sup>) or Arctic Deep Water (depths >900 m; 3-4 indiv/m<sup>3</sup>; 0.04 mg dry wt/m<sup>3</sup>). However, densities and biomasses in all three layers were very low when compared with shallower areas. In September of 1985 and 1986, we found a decrease in zooplankton biomass with increasing distance from shore and increasing water depth. In October 1986, the average zooplankton biomasses in the top 50 m of water over the mid-shelf area and



continental slope "were similar to those at our farthest offshore stations in September 1985, but were slightly higher than at similar September 1986 stations.

Zooplankton densities have been determined at many stations over the continental shelf in the Alaskan and Canadian Beaufort Sea. Table 22 compares the abundances (no./m<sup>3</sup>) of the major zooplankton groups collected in vertical and oblique tows during various studies in the Beaufort Sea. Overall, the abundances are much higher than the 56 indiv/m<sup>3</sup> reported by Hopkins (1969) for the Arctic Surface Layer of the Arctic Ocean farther north. Thus, the southern margin of the Beaufort Sea is apparently more 'productive' than the Arctic Ocean in general. This is to be expected since nearshore waters of the Beaufort Sea are relatively ice free during summer, and receive higher input of solar energy, and of nutrients from the land, than does the permanently ice-covered portion of the Arctic Ocean.

Zooplankton abundances off the Mackenzie Delta (avg: 1176 indiv/m<sup>3</sup>) and near Herschel Island (avg: 1103 indiv/m<sup>3</sup>) were higher than near Kaktovik in 1978 (avg: 137 indiv/m<sup>3</sup>), or in our study area during September of 1985 or 1986 (avg: 239 and 175 indiv/m<sup>3</sup>, respectively). However, sampling conducted near feeding bowheads in the eastern portion of our study area during September 1986 and along the Yukon Coast in August 1985 revealed high zooplankton abundances (avg: 1168 and 1266 indiv/m<sup>3</sup>, respectively), similar to the high abundances reported off the Mackenzie Delta and near Herschel Island (Table 22). The seemingly higher abundances in the Canadian Beaufort Sea may, in part, account for the fact that most Western Arctic bowheads apparently spend most of the summer feeding in the Canadian as opposed to the Alaskan Beaufort Sea. However, it must be stressed that the results in Table 22 are not totally comparable since the confounding factors of variable mesh size, tow type and sampling date cannot be eliminated.

#### Biomass of Zooplankton

Zooplankton biomass data from the Canadian and Alaskan Beaufort Sea are available from our study in 1985-86, from a similar study farther to the east in the Canadian Beaufort Sea in the same two years (Bradstreet and Fissel 1986; Bradstreet et al. 1987), and from an earlier study conducted near the Mackenzie Delta in 1980-81 (Griffiths and Buchanan 1982). All of these studies were conducted to document food availability to bowhead whales. Griffiths and Buchanan (1982) collected zooplankton opportunistically during August of 1980 and 1981 from a boat engaged in other work on bowheads. They were not able to sample systematically-selected stations. Their sampling locations and gear types differed between 1980 and 1981; in 1980 they used mainly vertical tows whereas in 1981 they integrated the results from horizontal tows at several sampling depths. In contrast, zooplankton sampling was the first priority of Bradstreet and colleagues in 1985-86. In both years they sampled at pre-defined stations along transects perpendicular to the coast using methods very similar to ours. Both the 1980-81 study of Griffiths and Buchanan (1982) and the 1985 study of Bradstreet and Fissel (1986) sampled within only a small portion of the nearshore and inner shelf waters of the Canadian Beaufort Sea. The 1986 study of Bradstreet et al. (1987) sampled a larger area, including waters off the Yukon coast, Mackenzie Delta and western Tuktoyaktuk Peninsula.

**Table 22.** Abundance (no./m<sup>3</sup>) of major zooplankton groups collected during various studies in the Alaskan and Canadian Beaufort Sea.

	Kaktovik <sup>a</sup>	Mackenzie Delta <sup>b</sup>	Herschel Island <sup>c</sup>	Yukon Coast <sup>d</sup>		Present Study, September <sup>e</sup>								October 1986 <sup>f</sup>	
				Whales Feed	Non-Feed	Nearshore		Inner Shelf		Outer Shelf		Whale Feed	Non-Feed	Mid-shelf	Deep Water
Date	Sept 78	Jul 73, Aug 91	Jul 73, Sept 74	Aug 85	Aug 85	Sept 85-86		Sept 85-86		Sept 85-86		Sept 86	Sept 86	Oct 86	Oct 86
Depth Range (m)	E-25	4-27	26-90	25	10-25	<20	#4	20-50	35-45	>50	>45	<30	<30	55	>1600
Mesh Size (μm)	505	73, 282	73, 579	505	505	505		505		505		505	505	505	535
Hydrozoans	4.2	3.5	0.5	0.9	1.4	1.8	0.4	2.8	0.1	1.7	1.0	1.6	2.3	3.1	1.4
Copepods	132	1149	1103	1263	266	646	497	75	21	23	16	1162	73	55	52
Mysids	0.5	7.5	48	2.3	0.7	1.2	0.3	x	-	x	-	4.3	x		
Amphipods	0.6	15.8	+	0.1	0.3	0.1	0.4"	1.0	0.1	0.6	0.3	0.2	0.3	0 . 2	0.2
Euphausiids	x <sup>h</sup>	-	-	x	0.2	0.5	x	x	x	x	-	-	x	0.2	0.2
Total	137	1176	1104	1266	269	650	498	79	21	25	17	1168	76	59	54
timber of tows	4	4	5	2	14	1	8	4	3	4	7	5	5	8	7

<sup>a</sup> Wrier (1979), double oblique tows, September data.

<sup>b</sup> Grainger and Grohe (1975), vertical tows, July-August data.

<sup>c</sup> Grainger and Grohe (1975), vertical tows, July-September data.

<sup>d</sup> Bradstreet and Fissel (1986), double oblique tows, August data.

<sup>e</sup> Present study (1985-S6), double oblique tows, September data.

<sup>f</sup> Present study (1986), vertical tows, October data.

g + means present but less than 1/m<sup>3</sup>.

h X means present but less than 0.1/m<sup>3</sup>.

Average Biomass in Water Column,--The best **sources** of data for general comparisons of the **zooplankton biomasses** from different areas and years are vertical or oblique tows. Mean **zooplankton biomasses** determined by oblique or **vertical** tows from the top 50 m of the water column show some consistency among years and **locations**, but there were also some noteworthy differences (Table 23). Samples collected during August 1980 in the Canadian **Beaufort** Sea contained the highest average **zooplankton** biomass; samples collected during October 1986 in the Eastern Alaskan **Beaufort** Sea contained the lowest. **Hydrozoans** and **ctenophores** dominated the 1980 samples and caused the high biomass. Excluding these two groups, mean biomass was  $161 \text{ mg/m}^3$  in 1980, about the same as that from other studies when **hydrozoans** and **ctenophores** were not dominant **zooplankters**. The average biomasses for the Canadian **Beaufort** Sea in 1981, 1985 and 1986 and the Alaskan **Beaufort** in September of 1985 and 1986 were remarkably similar. However, the methodology for the 1981 study was not directly comparable to that of the other studies.

Within the official study area, the overall average **zooplankton** biomass in the top 50 m of the water column decreased from September to October in 1986 (Table 23). However, the October samples were collected in the upper 50 m

Table 23. Comparison of mean zooplankton biomass in the top 50 m of the water column at various locations in the Alaskan and Canadian Beaufort Sea, 1980-86.

Location	Year	Month	mg/m <sup>3</sup>	n	Source
<b>Canadian Beaufort</b>					
E. Tuk Peninsula	86	Aug-Sept	210 <sup>b</sup>	10	Bradstreet et al. (1987)
Mackenzie Delta/ W. Tuk. Peninsula	80 81 86	Aug Aug Aug-Sept	632 (237) <sup>a</sup> 153 <sup>b</sup>	8 (11) 21	Griffiths and Buchanan (1982) Griffiths and Buchanan (1982) Bradstreet et al. (1987)
Yukon Coast	80 85 86	Aug Aug Sept.	166 211 <sup>b</sup> 173 <sup>b</sup>	4 16 15	Griffiths and Buchanan (1982) Bradstreet and Fissel (1986) Bradstreet et al. (1987)
<b>Alaskan Beaufort</b>					
Eastern Alaskan Beaufort	85 86 86	Sept Sept Ott	224 177 112	10 <sup>c</sup> 18 <sup>c</sup> 15 <sup>d</sup>	This study (Appendix 3) This study (Table 21) This study (Table 21)

<sup>a</sup> 1981 mean based on depth-integrated horizontal tows.

<sup>b</sup> Broad-scale transects only; includes whale feeding stations on pre-planned transects but not the special off-transect whale feeding stations sampled in 1985.

<sup>c</sup> Broad-scale transects only; excludes oblique tows to depths >50 m and 1986 samples from whale feeding stations and their controls.

<sup>d</sup> Only samples from Eastern Alaskan Beaufort Sea considered.

over waters 55 to 1730 m deep, with no sampling in **the** inner shelf or nearshore zones where biomass likely was higher. The average **zooplankton** biomass in the October 1986 samples from the official study area was higher than the biomass **at** the outer shelf stations during September.

Because **zooplankton** biomass in the Beaufort Sea can vary among and within **years**, and among locations, comparisons must be interpreted with caution. Specific comparisons of the September 1985 and 1986 results from this study and from **Bradstreet** and colleagues are warranted, because these two studies were conducted during the same years, at almost the same time of **year**, in two adjacent areas of the Beaufort Sea, and (in the case of oblique tows) with the same **type** of sampling gear. Bowheads were present near some sampling locations during our September **1986** work, and during **both** years of the study by Bradstreet and colleagues.

Mean **biomasses** in oblique tows taken during the two years and the two studies were remarkably similar (Table 23), although species composition varied somewhat (Table 24). Copepods accounted for 60-86% of the total biomass in the Canadian Beaufort Sea in 1985-86, vs. 73-75% of similar samples taken within our study area (Table 24). Although the group composition of the **zooplankton** was similar in both studies and years, the species composition of the **copepods** was quite different (Table 24). The small **copepod** *Limnocalanus macrurus* was the **dominant copepod** off the Yukon coast, especially in 1985, and off the Alaskan coast in 1986 but not 1985. The **large copepods** *Calanus hyperboreus* and *C. glacialis* accounted for most of the remaining **copepod** biomass in each area; they were the predominant **copepods** in the Alaskan samples in 1985, and off the Mackenzie Delta and Tuktoyaktuk Peninsula in 1986. The year-to-year differences in **copepod** species composition in our study area may have resulted from differences in the distributions of the water **masses** between 1985 and 1986, particularly in the nearshore area.

**Zooplankton Biomass vs. Water Masses.**--An evaluation of **zooplankton** biomass vs. water masses is confounded by a number of factors. For **example**, within our study area in 1985, the nearshore water mass was relatively narrow and restricted to water depths less than about 15 m. In 1986 the waters that we have classed as 'nearshore' covered a much wider area and encompassed depths from 10 to 34 m. Correspondingly, the 'inner shelf' zone (beyond the nearshore zone) was farther offshore in 1986 than in **1985**. Within **the** same year and area, water masses can and do change rapidly. **Also**, water masses **along** the Eastern Alaskan and Yukon coasts of the Beaufort Sea are not **always** directly comparable because **of** the differing influence of the Mackenzie River plume on each area. Comparisons of **zooplankton biomasses** in various water masses should be interpreted with these factors in mind.

In our study area, **zooplankton** biomass was low in surface and near-surface waters above the **pycnocline** (Table 25A). **Biomasses** at and near the surface were higher in the nearshore zone than in inner shelf or outer shelf waters (Table 25A). This may have been due to **the** greater influence of **Mackenzie** plume water, with its depauperate **zooplankton community**, in offshore waters, particularly in 1985. In the Canadian Beaufort Sea, **zooplankton** biomass in surface waters was much higher where Arctic Water was present at the surface than where Mackenzie plume water was present (Table 25B).

Table 24. Dominant zooplankton taxa taken in oblique bongo tows through the top 50 m of the water column along broad-scale transects in the Canadian and Alaskan Beaufort Sea. Whale feeding and control stations were excluded unless they were along pm--planned broad-scale transects.

	Canadian Beaufort Sea								Alaskan Beaufort Sea <sup>c</sup>			
	Yukon Coast 1985 <sup>a</sup>		Yukon Coast 1986 <sup>b</sup>		Mackenzie Delta 1986 <sup>b</sup>		E Tuk. Pen. 1986 <sup>b</sup>		1985		1986	
	mg/m <sup>3</sup>	%	mg/m <sup>3</sup>	%	mg/m <sup>3</sup>	%	mg/m <sup>3</sup>	%	mg/m <sup>3</sup>	%	mg/m <sup>3</sup>	%
Copepods	181	86	121	70	99	65	126	60	168	75	130	73
<u>Limnocalanus macrurus</u>	144	68	67	39	<1	<1	<1	<1	43	19	59	33
<u>Calanus hyperboreus</u>	15	7	27	16	74	48	97	46	80	36	17	10
<u>Calanus glacialis</u>	13	6	23	13	21	14	26	12	25	11	52	29
Mysids	8	4	7	4	7	4	5	2	5	2	1	1
Euphausiids	2	1	11	6	2	1	0	0	8	4	0.5	0.2
Hydrozoans + Ctenophores	7	3	18	10	24	15	35	17	22	10	15	8
Chaetognaths	4	2	6	3	5	3	17	8	6	3	4	2
Total	211		173		153		210		224		177	
Number of tows	16		15		21		10		10		18	
Max. Sample Depth (m)	10-25		10-50		9-50		9-50		10-50		8-50	
Station Depth (m)	12-171		14-167		10-68		12-52		13-80		10-205	

<sup>a</sup> Bradstreet and Fissel (1986).

<sup>b</sup> Bradstreet et al. (1987).

<sup>c</sup> This study, considering only stations with oblique tows to depths <50 m.

Table 25. Mean total biomass ( $\text{mg}/\text{m}^3$ ) of zooplankton collected (A) on broad-scale transects in this study, 1985-86, and (B) in the Canadian Beaufort Sea, 1985-86.

		Geographic Zones							
		Nearshore		Inner Shelf		Outer Shelf		'Polar Star' 1986	
Depth zone	Type of Tow	1985	1986	1985	1986	1985	1986	Mid Shelf	Beyond Shelf
<b>A. This Study<sup>a</sup></b>									
<b>Above Pycnocline</b>									
Surface	Her.		70	-	13	-	12		
Below Surface	Her.	131	301	46	20	14	43		
<b>Below Pycnocline</b>									
Arctic Water <sup>b</sup>	Her.	463	2181	448	659	136	312		
Bering Water	Her.						2	2	5 - -
Top 50 m of Water Column	Obliq. or Vert.	487	296	209	170	133	43	124	100
<b>B. Bradstreet et al. (1987)<sup>c</sup></b>									
		Diffuse Plume		Diffuse/Arctic		Arctic Water			
		1985	1986	1985	1986	1985	1986		
Surface	Her.		59	9	-	12	1008	73	
Within Zoopl. layers	Her.		71	35	-	104	462	229	
Top 50 m of Water Column	Obliq.		202	142	243	221	170	326	

<sup>a</sup> Broad-scale transects only; whale feeding and control stations are excluded.

<sup>b</sup> Samples taken within and outside zooplankton layers are pooled.

<sup>c</sup> Broad-scale transects only; whale feeding stations not on pre-planned transects are excluded.

Arctic Waters below the pycnocline contained much higher biomasses than did surface waters during both years of our study. The average biomass found in the Arctic Water in the Canadian Beaufort Sea was comparable to biomasses in Arctic Water in our study area. "As in surface waters, the average zooplankton biomass in Arctic Waters appeared to decrease with increasing distance from shore (Table 25A).

Biomass Near Feeding Bowheads. --Zooplankton samples have been collected near feeding bowhead whales in the Canadian Beaufort Sea in 1980-81 (Griffiths and Buchanan 1982) and in 1985-86 (Bradstreet and Fissel 1986; Bradstreet et al. 1987), and in the Eastern Alaskan Beaufort Sea in September 1986 (this study). The opportunistic sampling by Griffiths and Buchanan (1982) showed that average zooplankton biomasses near whales were somewhat higher than the regional mean (558 vs. 476 mg/m<sup>3</sup> in 1980; 499 vs. 237 mg/m<sup>3</sup> in 1981). The more comprehensive studies in 1985-86 showed that mean biomasses in the whole water column were much higher at whale feeding locations than at other locations (Alaska 1986: 828 vs. 177 mg/m<sup>3</sup>; Yukon Coast 1985: 562 vs. 160 mg/m<sup>3</sup>; Canadian Beaufort Sea 1986: 532 vs. 130 mg/m<sup>3</sup>; Fig. 106, Table 26). The differences in biomasses between whale feeding locations and other areas were attributable to differences in the abundance of copepods. The total biomasses of all other groups of zooplankton were virtually identical at whale feeding areas vs. other locations in both areas and years (Fig. 106).

The small copepod Limnocalanus macrurus (adults <2 mm in length) dominated the zooplankton biomass in the water column at all nearshore locations where whales were feeding. It represented 26-97% of the total biomass at feeding sites near the Yukon and Alaskan coast in 1985-86. Previous work had suggested that bowheads feed on larger copepods and other macro-zooplankters (Lowry and Frost 1984). However, Bradstreet and Fissel (1986) suggested that bowhead whales must be able to feed on copepods <2 mm in length, since they comprised most of the zooplankton biomass in areas where bowheads were observed feeding in 1985. The same argument would apply for whales feeding along the Alaskan and Yukon coasts in 1986, where L. macrurus was again the major contributor to the zooplankton biomass at whale feeding locations. The fact that bowhead whales are able to feed on these small copepods was confirmed by Lowry et al. (1987). Small copepods (1.1 to 1.9 mm in length) of the genera Limnocalanus, Pseudocalanus and Jaschnovia were major food items in the stomach of bowhead 86KK1, taken in nearshore waters within our study area on 10 September 1986.

Food availability in concentrated layers of zooplankton is more relevant to bowheads than are the above-noted average biomasses in the water column as a whole. At most locations sampled in this study, we found that zooplankton biomass in one or more layers was much higher than the average for the water column as a whole. This was evident both from the hydroacoustic surveys and from horizontal vs. oblique tows (see 'Results'). These differences were also evident at specific locations where feeding bowheads were observed during 1985-86 (Table 26). Biomasses within these concentrated layers at most whale feeding locations exceeded 1 g/m<sup>3</sup> and reached a maximum of approximately 3 g/m<sup>3</sup> at our Station 86-5. During September 1986, high density layers were more common at whale feeding locations than in the region as a whole. Seven of

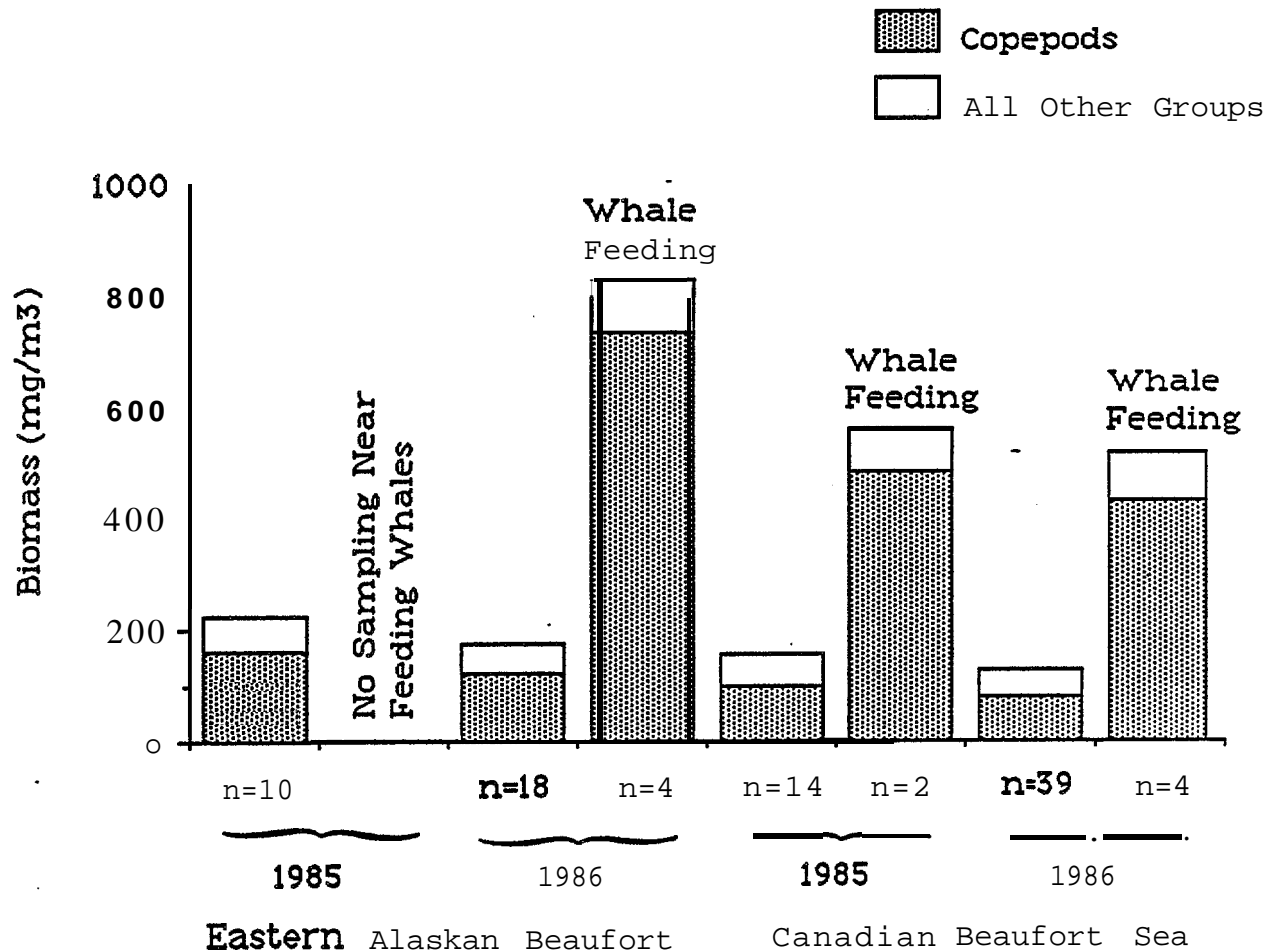


FIGURE 106. Comparison of average biomass ( $\text{mg}/\text{m}^3$ ) in the top 50 m of the water column at whale feeding stations vs. stations along broad-scale transects, Eastern Alaskan Beaufort Sea and Yukon Coast, 1985-86. Only the top 35 m of the water column was sampled along the Yukon Coast in 1985. For each situation, n is the number of oblique zooplankton tows. See Table 26 for list of whale feeding stations considered here.



**Table 26. Mean biomass (mg/m<sup>3</sup>) of zooplankton in the entire water column and in the densest zooplankton layer at each station where zooplankton available to feeding bowhead whales was studied in the Alaskan Beaufort Sea during 1986 (this study) and the Canadian Beaufort Sea during 1985-86 (Bradstreet and Fissel 1986; Bradstreet et al. 1987). Includes only the stations where whales were feeding near the boat at the time of sampling.**

Location	Station	Year	Month	Water Column Average mg/m <sup>3</sup>	Layer of Highest Density	
					Biomass mg/m <sup>3</sup>	% Copepods
Alaska	86-5	1986	Sept	1228	3023	97
	86-7, 86-9	"	Sept	853, 318	2886	83
	86-12	"	Sept	912	2137	97
Yukon	14	1985	Aug	288	1098	95
	2	"	Aug		2142	99
	3	"	Aug	836	1203	97
	26	"	Aug		2294	98
	2	1986	Sept	776	1543	99
	3	"	Sept	455	771	64
Mack. Delta	60	"	Aug	369	-a	
Tuk. Pen.	79	"	Sept	527	-a	

a Echosounder not functioning so net could not be guided to densest layer.

ten recognizable layers at feeding stations had biomasses that exceeded 1 g/m<sup>3</sup>, while only 4 of 24 layers identified at stations along the broad-scale transects exceeded this biomass,

In all cases, copepods were by far the major contributors to zooplankton biomass (64 to 99%) in the concentrated layers at whale feeding stations in our study area and in the Canadian Beaufort Sea (Table 26). In all cases where copepods were identified to species, Limnocalanus macrurus was the dominant copepod (26 to 97% of total biomass in water column) at whale feeding stations along both the Alaskan and Yukon coasts. However, Calanus hyperboreus and C. glacialis dominated in samples taken near bowheads off the Mackenzie Delta and Tuktoyaktuk Peninsula in 1981 and 1986 (Griffiths and Buchanan 1982; Bradstreet et al. 1987).

Average zooplankton biomass in the Eastern Alaskan Beaufort Sea during September of 1985-86 was not greatly different from that in the Canadian Beaufort Sea during the same period. In 1985, most waters along the Alaskan coast contained relatively low biomasses of zooplankton, with only occasional

dense layers scattered throughout the water column (Griffiths et al. 1986). Within the official study area, few bowheads were observed from the aircraft in early-mid September 1985, and only one was seen from the boat. Whether the low number of bowheads that apparently used our study area for feeding in early-mid September 1985 was due to the low zooplankton biomasses in the area cannot be determined. However, during 4-7 September 1986, **zooplankton** biomasses typically were high and **zooplankton** layers were thick in nearshore shallow waters (depths <25 m) in the southeastern portion of our study area. Numerous bowheads were feeding **in** that area between 4 and 7 September. **Zooplankton** biomasses were lower and **layers** were thinner along the broad-scale transects from 10 to 19 September 1986. Few bowheads were seen from the boat along these broad-scale transects in mid September 1986.

The overall results suggest that **zooplankton** concentrations containing **biomasses** that would be energetically profitable for bowhead feeding occur in portions of the study area in some but not **all** years. The overall importance of the Eastern Alaskan Beaufort Sea to individual bowhead whales and to bowheads in general is discussed in the 'Integration' section, p. 449 ff).

#### Caloric Content of Zooplankton

The caloric content of copepods and other **taxa** collected during this study was similar to that reported for other **arctic** areas. Considering all copepods collected in 1985, the caloric content in our study area appeared to be **slightly** greater than that **in the** Canadian Beaufort Sea (Table 27;  $t' = 2.19$ ,  $df = 33$ ,  $p < 0.05$ ). In 1986, **caloric** content of all copepods averaged about 1200 **cal/g** greater in our study area than in the Canadian Beaufort Sea ( $t = 9.9$ ,  $df = 109$ ,  $p < 0.001$ ). The Canadian collections were made only about two weeks earlier than ours in both years, and it is not certain whether seasonal, regional or methodological differences account for the differences.

'Caloric content' of copepods collected in October was about 1600 **cal/g** **lower** than that of copepods collected one month earlier **in** the same area (Table 27). Copepod biomass in **the** upper 50 m was very **low** in October. Most copepods had probably descended to overwintering depths >50 m. At this time of year, **lipid** content of **copepods** at depths >200 m is higher than in **copepods** at depths <50 m (Head and Harris 1985). Presumably animals remaining in the upper 50 m had not yet stored sufficient reserves for winter, and had a lower caloric content than those at depth.

During the season of peak productivity, caloric and **lipid** content of copepods can change by a large amount over a short period of time, especially in spring. Lee (1974) found that lipid content of Calanus hyperboreus from the Arctic Ocean increased by 80 percent between June and July. Changes in **lipid** content were less dramatic later **in** the season; between **August and** September, lipid content dropped by 11 percent. In Frobisher Bay, caloric content of copepods increased by 12 percent between late July and **late** September. In the Bering Sea, caloric content of the euphausiid Thysanoessa increased by only 24 percent between spring and **fall**.

Head and Harris (1985) believe that once Calanus hyperboreus has stored enough food to meet **the** requirements of **overwintering** and spring egg production, there is no further increase in lipid **storage--i.e.**, there may be

Table 27. Caloric content (cal/g dry wt.) of copepods from arctic regions, Bering Sea, and North Atlantic Ocean.

			Mean	± s.d.	n
<b>Late Summer Data</b>					
Alaskan Beaufort Sea (this study)	1986 Sept, all copepods		6297 ± 619		47
	October, all copepods		4718 ± 351		13
	1985 Large copepods (>1.8 mm)		7368 ± 406		17
	Small copepods (<1.8 mm)		6635 ± 483		10
	All copepods		7096 ± 559		27
Canadian Beaufort Sea (Bradstreet and colleagues 1986-87)	1986 Large Copepods (>1.8 mm)		5080 ± 653		54
	Small Copepods (<1.8 mm)		4712 ± 910		10
	All copepods		5023 ± 704		64
	1985 Large Copepods (>1.8 mm)		6867 ± 107		3
	Small Copepods (<1.8 mm)		6840 ± 163		11
	All copepods		6845 ± 149		14
Frobisher Bay (Percy and Fife 1980)	<u>Calanus</u> spp. (large) <sup>a,c</sup>		7690 ± 310		4
<b>Other Seasons</b>					
Bering Sea (Harris 1985)	<u>Neocalanus cristatus</u> <sup>a</sup>		6186 ± 953		8
	<u>Metridia pacifica</u> <sup>b</sup>		5166 ± 462		3
	Average copepod (average of 6 species)		5912		
Lancaster Sound (Bradstreet 1982 )	Calanoid copepods <sup>a</sup>		6537 ± 834		7
North Atlantic (Laurence 1976)	<u>Calanus finmarchicus</u> <sup>a</sup>		6425 ± 187		3
	<u>Pseudocalanus minutus</u> <sup>b</sup>		5071 ± 182		3

<sup>a</sup> Large copepods >1.8 mm.<sup>b</sup> Small copepods <1.8 mm.<sup>c</sup> September samples.<sup>d</sup> August samples.

a maximum **lipid** content for a particular overwintering life stage. If most arctic **zooplankters** have a similar life cycle, then increases in lipid content in the fall could be minimal.

In both the Eastern Alaskan and Canadian Beaufort Sea, caloric content of **copepods** was significantly **lower** in 1986 than in 1985 ( $t = 5.53$ ,  $df = 72$ ,  $p < 0.001$  for Eastern Alaskan **Beaufort**,  $t' = 18.9$ ,  $df = 78$ ,  $p < 0.001$  for Canadian **Beaufort**). In the Canadian Beaufort Sea, **lipid** content of **copepods** was also lower in 1986 than in 1985 (Bradstreet et al. 1987). These results suggest **that** copepods had consumed less food in 1986 than in 1985. The timing and magnitude of changes in caloric content depend on the timing of primary production. When the productivity cycle begins early, copepods may have stored overwintering reserves early and late summer increases may be minimal. Late summer increases could be large if the start of the spring bloom were delayed. Thus, **annual** differences in the primary productivity regime **could** account for year-to-year differences in caloric content of **copepods** at a particular **time of year**.

**Annual** differences in the quantity of primary production could **also** account for annual differences in caloric content. In the high arctic, copepods may be able to adjust their **life** cycles according to quantity of food that is available (Cairns 1967). Reproduction is delayed until the **copepods** have stored sufficient energy for egg production. Under these circumstances, caloric content would be low in a year when primary productivity was low.

The total caloric content of **copepods** per unit weight would not be as important to feeding whales as the total energy available per unit **volume** of water. Even though caloric content of copepods was **lower** in 1986 than in 1985, maximum concentrations of potential food organisms (**in terms of cal/m<sup>3</sup>**) were greater in 1986 than in 1985.

#### Fronts and Other Concentrating Mechanisms

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Mean biomass of zooplankton, as determined from the echosounder data, was similar in 1985 and 1986 (Table 16). However, there were differences in **the** distribution **of** patches containing a high biomass of zooplankton. **The** distribution of sub-surface oceanographic properties was also **different** in the two years and these differences may have affected the locations of **zooplankton** patches. In 1986, apparent biomass was highest **on** the outer **shelf** of Transect T1. This high biomass, if real, may have been due to strong sub-surface frontal development caused by the intrusion of Bering Sea Water into the study area. The influence of this intrusion decreased east of Transect T1, and estimated zooplankton biomass was **lower** along the outer shelf portions of transects T3 and T4. In 1985 the higher biomass found in the nearshore zone than farther offshore **could** have been related to coastal **upwelling** present during and before the time of sampling (see 'Water Masses'). With these two exceptions, broad-scale distributions of zooplankton biomass appeared to have been quite similar in 1985 and 1986 (Table 16).

Oceanic fronts are boundaries between water masses of different properties. Most of the 'fronts' noted in this study were **discontinuities** of surface properties. These discontinuities did not extend much below the surface and apparently had no major effect on the distribution of **zooplankton**.

Some sub-surface fronts were also present:

1. In 1986 only, a **front** between Bering Sea Water and **cold** Arctic Water, located around the 50 m contour and diminishing in intensity to the east.
2. A front between **cold** saline Arctic Water and water of Mackenzie River origin, located in **the** southeastern part of the study area in 1986 and along much of the nearshore zone **in 1985**.

A seasonal **thermocline** was also present in **the** study area in 1985 and 1986.

Our data on zooplankton aggregations associated with sub-surface discontinuities in temperature and salinity are **less** detailed than we would like. This was partly a result of the difficulties in characterizing subsurface physical gradients; even the rather closely spaced CTD stations occupied in 1986 did not provide adequate horizontal resolution for this purpose. Another limitation was the questionable reliability of **hydroacoustic** data in areas with strong physical gradients. This has proved to be an even more serious problem in the Canadian Beaufort Sea, where physical gradients tend to be stronger than in the Eastern Alaskan Beaufort Sea (Bradstreet et al. 1987). In 1987, an investigation of echosounder performance 'for zooplankton sampling is to be done in the Canadian Beaufort Sea (D. Fissel and M. Bradstreet, pers. comm.). It is hoped that their 1987 study will lead to improved methods for measuring zooplankton biomass and patchiness in the Beaufort Sea.

In 1986, zooplankton biomass was highest and dense patches of zooplankton were most common at locations where feeding whales were observed. The **structure** of the water column at these stations was complex. Strong vertical and horizontal gradients were caused by the presence of warm **turbid** water of Mackenzie River **origin** adjacent to **cold saline** Arctic Water. These **strong** gradients appear to have provided an aggregating mechanism for zooplankton, making the area attractive to feeding **bowheads**. Fissel et al. ('Water Masses' section) do not believe that strong gradients of these types existed in the nearshore portion of the study area in 1985. The presence of strong horizontal **temperature** and salinity gradients in the **study** area may be important for the formation of zooplankton patches that are of sufficient magnitude and density for efficient **bowhead** feeding.

There is considerable year to year variability in the distribution of water masses in the Beaufort Sea (Thomson et al. 1986). The results of this study and the simultaneous Canadian studies indicate that **the** distributions of these water masses strongly influence the **distribution** of zooplankton. **Bowhead** whale distributions appear to **be** strongly linked to the distribution of **their** prey and thus to water properties.

#### Conclusions

1. The group and species composition of the zooplankton in the Eastern Alaskan Beaufort Sea, during September of 1985-86 and October 1986, was similar to that elsewhere along the Beaufort Sea coast and in

other arctic regions. However, relative abundances of some species and groups vary between locations and years.

2. Copepods dominated the **zooplankton** along the broad-scale transects during September 1985-86, representing 78 and 81% of the wet weight, respectively, and 87 and 98% of the individual **zooplankters**. In October 1986, copepods accounted for **85%** of the individuals but only 24% of the biomass in the upper 50 m of the **water** column over the mid-shelf and continental slope in our main study area.
3. In September 1985, the large (>1.8 mm in length) copepods **Calanus hyperboreus** and **C. glacialis** were the dominant contributors to **total zooplankton biomass**, while in September 1986 the small (<1.8 mm in length) copepod **Limnocalanus macrurus** was the dominant contributor. In both years, **Limnocalanus** dominated in nearshore waters and **Calanus** dominated farther offshore; the nearshore zone where **Limnocalanus** was abundant was more extensive in 1986. ,
4. In both years, euphausiids and mysids were most abundant near the bottom in nearshore waters. Whether they also occurred in similar abundances near the bottom farther offshore is not certain, since few near-bottom samples were taken offshore. In October 1986, euphausiids were much-more abundant farther west, between Pt.- Barrow and Prudhoe Bay, than in the official study area.
5. In September 1985-86, average **zooplankton** biomass was highest in the nearshore and inner shelf areas (south of the 50 m contour), and **lower** on the outer **shelf** (north of the 50 m contour). Biomass in the intrusion of Bering Sea Water over the outer shelf in 1986 was unremarkable.
6. Biomass **in** the top 50 m over the continental slope (near 1800 m contour) was similar to that over the outer shelf, and much higher than previously reported for the top 200 m of the Arctic Ocean far offshore (cf. Hopkins 1969).
7. The average **zooplankton** biomass in the top 50 m within our study area was similar in both years, about 200 **mg/m<sup>3</sup>**. Our average biomasses were similar to those over the continental shelf of the Canadian Beaufort Sea during late August-early September 1985-86 (cf. **Bradstreet et al.** 1987).
8. **Hydroacoustic** surveys showed that zooplankton distribution was patchy in both years. Patches tended to be more abundant in nearshore and inner shelf waters (<45 m deep) than over the outer shelf. Average **zooplankton biomass** within patches was **also** higher in nearshore and inner shelf areas than farther offshore.
9. **Zooplankton** patches often extended for several kilometers in the horizontal plane, but usually were only 5-10 m thick. Patches along broad-scale transects were typically more extensive in the horizontal plane in September 1985 than in September 1986.

10. Bowhead whales were **absent** during **zooplankton** sampling in 1985. Feeding **bowheads** were present in nearshore **waters** in the **SE** corner of **the** study area (and to **the** east along the **Yukon coast**) in **early** September 1986. In 1986, average **zooplankton** biomass was higher at five whale feeding stations than **at** corresponding control stations. Average biomass at our **whale** feeding stations was similar to that at **whale** feeding stations farther east along **the** Yukon coast in 1985-86 (**cf.** Bradstreet et al. 1987). Bowheads **usually** feed in areas where **zooplankton** biomass is **about**  $1-3 \text{ g/m}^3$  **at** the depth of maximum biomass,
11. In **all** cases the higher **zooplankton** biomass **at** **whale** feeding stations was due to unusually high **copepod** biomass. The biomass of **all** other **zooplankters** combined was similar **at** **whale** feeding and control stations.
12. Limnocalanus macrurus was the dominant copepod in **layers** of concentrated **zooplankton** at whale feeding stations along both the Alaskan and the Yukon coasts. These **small copepods**, <2 mm in length, can be filtered from the water by bowhead whales; L. macrurus was a major food item in the stomach of one bowhead **taken** in nearshore waters within our study area in September 1986.
13. Although dense **layers** of concentrated **zooplankton** were most common in nearshore **waters**, especially **near** feeding **bowheads**, such **layers** did **occur farther** offshore over **the** continental **shelf**. Other **taxa**, **usually** Calanus, dominated in these patches. Although these patches were **not being** used by feeding bowheads during our **zooplankton** sampling periods, they presumably are used at other times.
14. In **September** 1985-86, **zooplankton** biomass was very **low** in surface and near-surface **waters**. The majority of **zooplankters** were between the **pycnocline** and a depth of 45 m, except **at** some nearshore **stations** where the **pycnocline layer** was continuous from a few meters depth to the bottom. **Most zooplankters** were in **one** or more **layers** a few meters **thick at** mid-water or near-bottom positions. This was true **at** **whale** feeding and control stations as **well as** **along** broad-scale transects. Consistent with this, **almost all** whales observed feeding in the **study** area **per se** were feeding in the water **column**, below the surface.
15. At **whale** feeding stations, **zooplankton** patches tended to be thicker **than at** corresponding control stations and often stretched from **just below** the surface to the bottom.
16. In **September** 1985, **zooplankton** biomass was slightly higher within than **outside** frontal **areas**. In **September** 1986, there was no such relationship. However, **the** subsurface concentrations of **zooplankton** in the nearshore feeding **areas** were **within** cold **saline** waters overlain **by** much warmer turbid **water**, and inshore of areas where subsurface waters were slightly warmer and **less** saline.

17. **Copepods** had a higher energy content per unit weight than other major groups. Copepods contributed 90 and 89% of the **total** caloric content of the zooplankton in 1985 and 1986, respectively. **Caloric** content per gram of **zooplankton** was higher in 1985 than in 1986, and higher **in** our study area than in the Canadian Beaufort Sea about two weeks earlier.
18. Along broad-scale transects, mean caloric content of the zooplankton in **the** top 50 m, on a 'per cubic meter' **basis**, was similar **in 1985** and **1986: 225 vs. 179 cal/m<sup>3</sup>**, respectively. **At** whale feeding **stations**, mean caloric content was **much** higher, **643 cal/m<sup>3</sup> in the** water **column** as a whole and **2132 cal/m<sup>3</sup>** in concentrated layers of **zooplankton**.



## BOWHEAD DISTRIBUTION, NUMBERS AND ACTIVITIES\*

Introduction

Bowhead whales of the Western Arctic population migrate westward through the study area in early autumn while en route from their main summering areas in the Canadian Beaufort Sea to their wintering grounds in the Bering Sea (see Fig. 1 on p. 2). Aerial surveys have shown that a few bowheads occur in the study area during August of some years, but that bowheads do not become common there until September. Migration through the area is largely completed by mid October (Ljungblad et al. 1986c). Some of the whales moving westward through the study area, particularly during the early stages of migration, do not travel strongly or consistently. At least some whales feed at this time (Ljungblad et al. 1986a).

Previously Available Information

Pre-1985 data on the utilization of the Eastern Alaskan Beaufort Sea by bowhead whales were summarized by Ljungblad et al. (1985a, 1986a-c) and by LGL and Arctic Sciences (1985). Since 1979, aerial surveys for bowheads have been conducted in this area during late summer and early autumn of each year. In 1979-81 the coverage was mainly in nearshore areas and there was little coverage of our study area before 1 September. From 1982 to date, the survey coverage has extended far offshore and has included most if not all of the period of westward migration. In most years, more whales have been seen per hour of surveying in the nearshore portion of our study area than in any other part of the Alaskan Beaufort Sea (Ljungblad et al. 1986c, p. 80-84).

Bowheads were seen in the Eastern Alaskan Beaufort Sea during August in some years, especially 1982, but not in all years. Considering our official study area only, the dates of first, and last sightings (as summarized by LGL and Arctic Sciences 1985) were as follows:

<u>Year</u>	<u>First Sighting</u>	<u>Apparent Peak</u>	<u>Last Sighting</u>
1979	20 Aug	24-26 Sept	6 Ott
1980	4 Sept	14 Sept	21 Sep
1981	7 Sept	12-29 Sept	9 Ott
1982	2 Aug	6 Aug - 24 Sept	6 Ott
1983	2 Aug	2 Aug - 6 Sept	2 Ott
1984	15 Aug	4-26 Sept	10 Oct

Bowheads may have been present earlier or later in some years, especially 1979-81 when survey coverage was most limited. No bowheads were seen farther west before the dates of first sightings listed above, but a few were still present farther east in mid October 1982 (Ljungblad et al. 1983).

Bowheads seen in the Eastern Alaskan Beaufort Sea during August were generally not traveling actively westward. They tended to be farther offshore than bowheads seen there in September-October. The same trend was evident for

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\* By W. John Richardson, B. Würsig and G.W. Miller.

the Alaskan **Beaufort** Sea as a **whole** (Fig. 107; Ljungblad et al. 1986c, p. 92-95) .

Pronounced westward migration through our study area usually begins in **early** or mid September and continues until early or mid October. Most whales **travel** west over the mid-shelf region, but some **travel** west through shallow nearshore waters, and others are far offshore near or beyond the shelf break (Fig. 107). In one year, 1983, the westward migration through the study area and elsewhere tended to be farther offshore than in **all** other years since 1979. Considering September and October data **only**, median depths at sighting locations in and near the study area (longitudes 141°-146°W) were 732 m **in 1983**, as opposed to 33-49 m in other years from 1979-84 (Ljungblad et al. 1986c, p. 102). The unusual pattern **in** 1983 may have been related to heavy ice **cover** in that year.

Bowheads that were believed to be feeding have been seen during late summer and autumn at many locations across the Alaskan Beaufort Sea. During the 1970's, groups of feeding bowheads were seen just east of Barrow on several occasions (Braham et al. 1984; Ray et al. 1984). However, during 1979-84, Ljungblad et al. (1986a) found that feeding was more common and consistent in **the** Eastern Alaskan Beaufort Sea than farther west. Although the distribution of feeding and non-feeding whales overlapped, feeding whales tended to occur closer to shore (Fig. 108).

Up to 1984, 'definite' observations of feeding bowheads **within** the study area were confined to waters less than 200 m deep, and mainly to waters less than 50 m deep (Fig. 108, 109). The dates of these observations ranged from 12 to 29 September (**or** perhaps as **early** as 9 Sept in 1980, Lowry and Frost 1984, p. 11). Within the continental shelf zone, specific locations where feeding occurred seemed to vary among years. However, the data on feeding **in** 1979-84 were obtained incidental to studies with other purposes. Thus, the available data for 1979-.84 do not provide detailed information about within- and between-season changes in utilization of specific areas.

Although **all** 'definite' observations **of** feeding bowheads within the study area up to 1984 were over the continental shelf during mid-late **September**, feeding may sometimes occur in deeper waters and **in** August. Groups of **bowheads** have sometimes been seen two or more times. over periods of several days **in** deeper parts of the study area, often in August (summarized in LGL and Arctic Sciences 1985, p. 15-21). There is no proof that the same individuals were present from one date to the next, or that these whales were feeding. However, these observations suggest that feeding may occur in the continental **slope** portion of the study area ("depths 200-2000 m) on some occasions, particularly **in August**.

Stomach contents of bowhead whales harvested during early autumn at Kaktovik (in the study area, n = 8) and at Barrow (n = 2) have been described by Lowry and Frost (1984). **All** of these **whales** had been feeding recently, mainly on copepods, euphausiids, or **both**. At Kaktovik, the composition of the stomach contents varied widely among whales, with as much as 99.7% copepods **in** some whales, and as much as 97.9% euphausiids in others. Of the whales taken at Kaktovik and described by Lowry and Frost (1984); the three containing significant amounts of **euphausiids** were **all** taken in 1979.

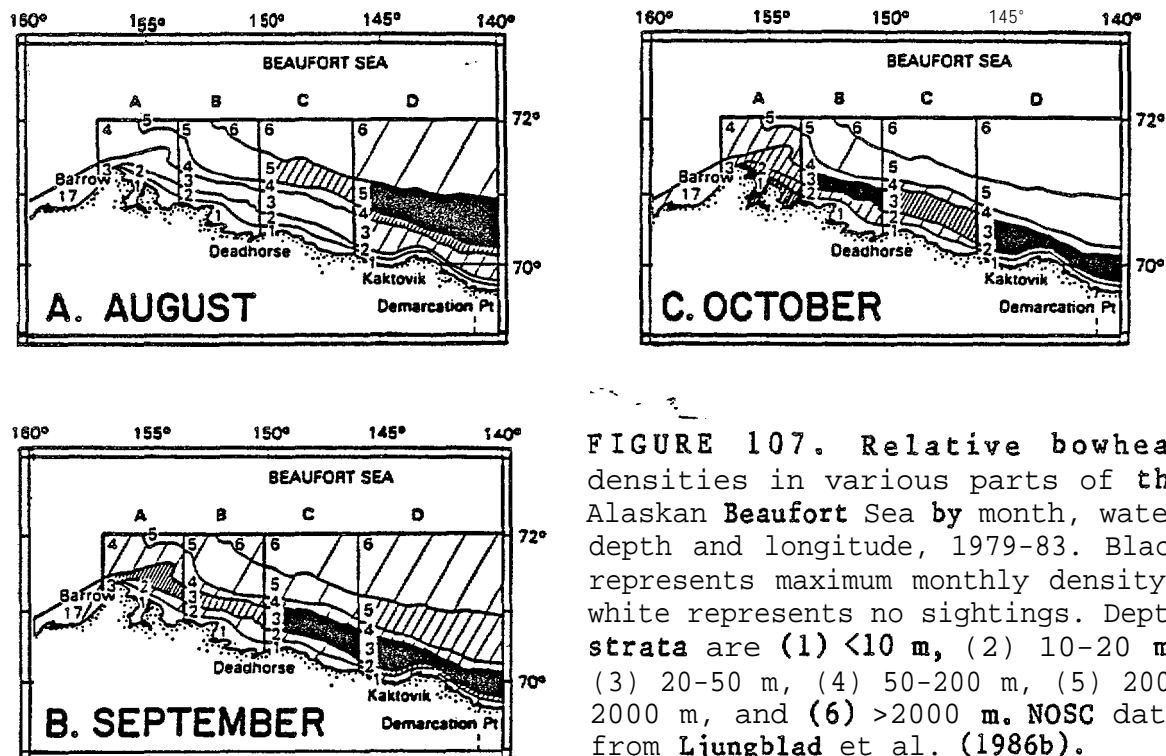


FIGURE 107. Relative bowhead densities in various parts of the Alaskan Beaufort Sea by month, water depth and longitude, 1979-83. Black represents maximum monthly density; white represents no sightings. Depth strata are (1) <10 m, (2) 10-20 m, (3) 20-50 m, (4) 50-200 m, (5) 200-2000 m, and (6) >2000 m. NOSC data from Ljungblad et al. (1986b).

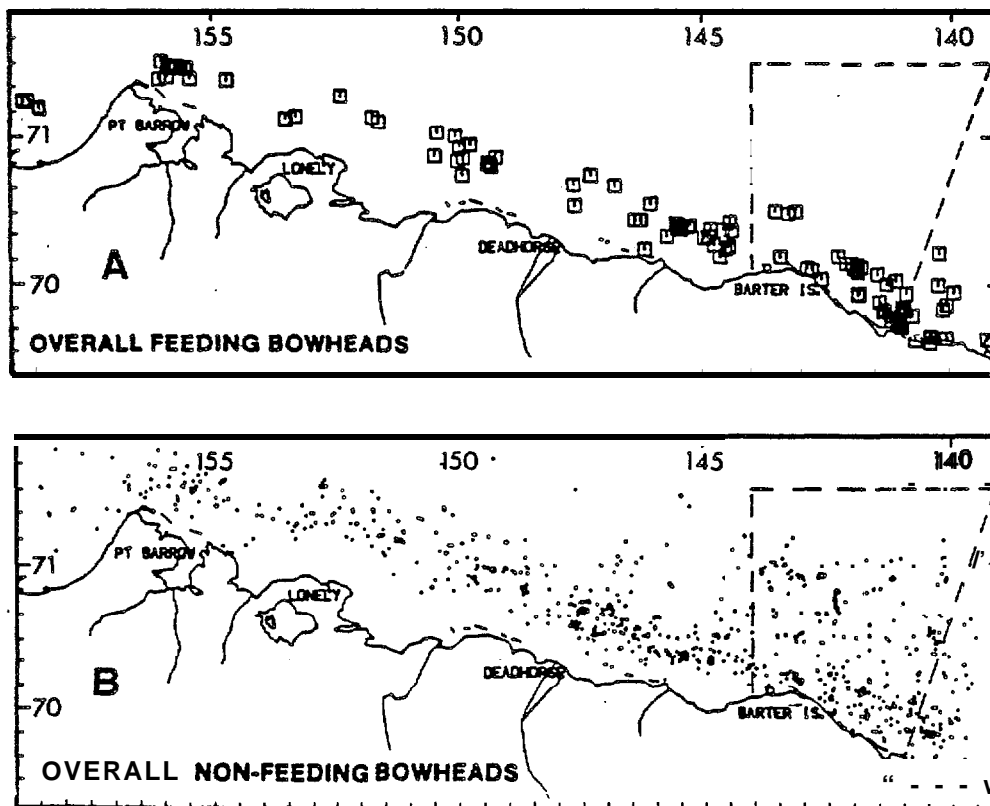


FIGURE 108. Sightings of (A) feeding and (B) non-feeding bowheads in the western and central Beaufort Sea, late summer and autumn, 1979-84. NOSC data, from Ljungblad et al. (1986a).

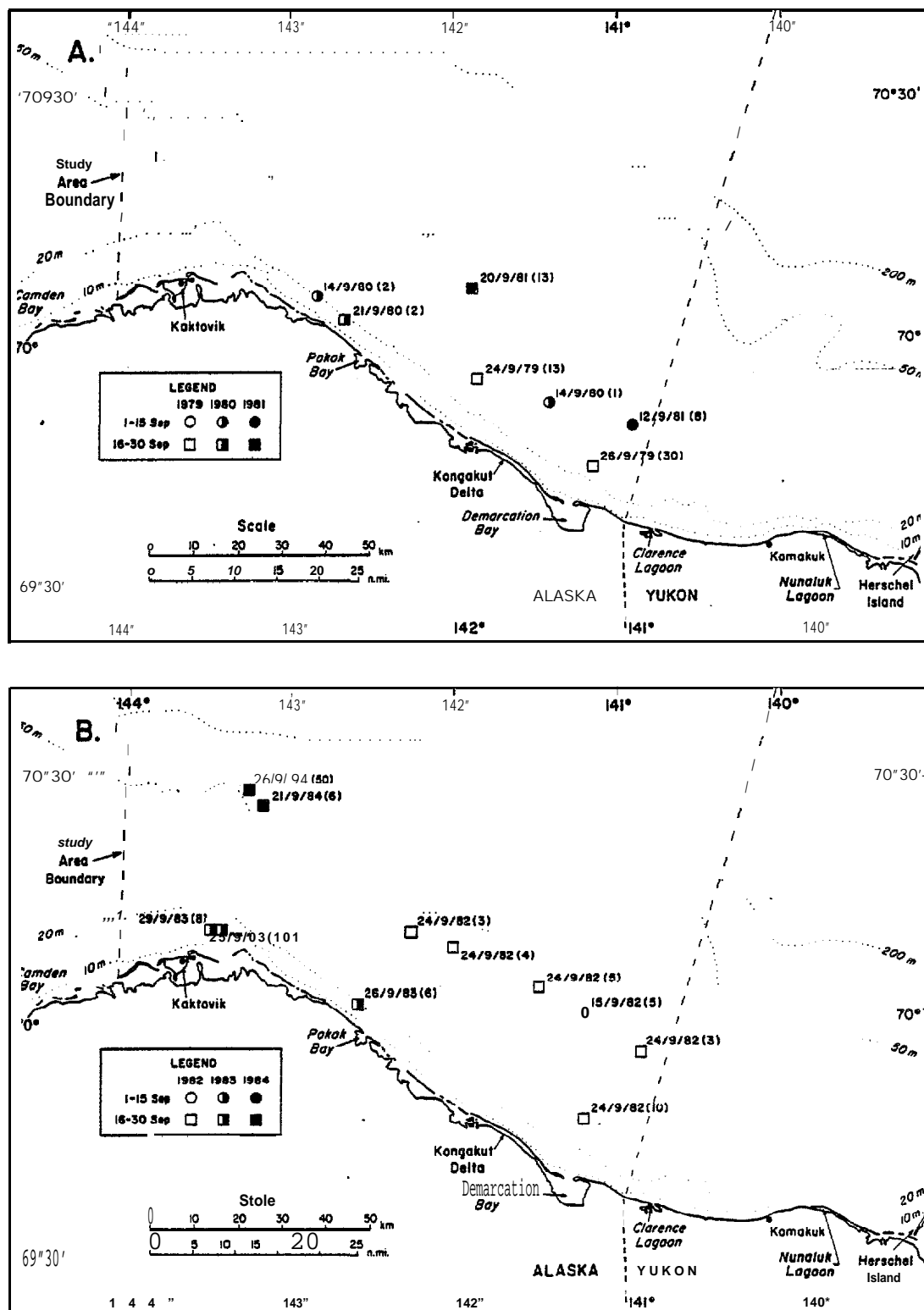


FIGURE 109. Locations of feeding bowhead whales seen within the official study area, (A) 1979-81, and (B) 1982-84. Dates and (in parentheses) numbers of whales are shown. From LGL and Arctic Sciences (1985, p. 10-14), including NOSC and LGL data.

### Limitations of Previously Available Data

Previous aerial surveys have provided valuable data on the routes and **timing** of bowhead movements through the study **area**, and some observations of feeding. However, utilization of **the** study area has not been documented on a quantitative basis:

1. **The** average distribution **and** timing of occurrence of bowheads in the study area are relatively **well** known (Ljungblad et al. 1980-85a; Richardson et al. 1985a, 1987). However, distribution and times of occurrence within the study area vary somewhat from year to **year**, and cannot be predicted. For **example**, whether or not significant numbers of **bowheads will** be present in **August** of any given year is **not** predictable. Variation in ice cover may affect the timing and routes of autumn migration (Ljungblad et al. 1984a, 1986b). **We** hypothesize **that** some of the remaining variation is related to **annual** and seasonal differences in food availability within and east of the study area.
2. Aerial surveys by Ljungblad et al. (1980-85a) have documented **the** relative numbers of bowheads in various parts of **the** Eastern Alaskan Beaufort Sea during different years and months. However, absolute numbers of whales there have not been estimated for any specific time. Absolute estimates are difficult to obtain because allowance **must** be made for the many **whales that** are inevitably missed **during** **aerial** surveys. Correction factors must be determined to **allow** for whales at the surface but **not** seen, and for **the many whales below the** surface as the survey aircraft passes. Prior to this study, correction factors had been derived for **aerial** surveys of the Canadian summering grounds in 1981 (Davis et al. 1982), but **not** for other areas or **years**.
3. **The** composition of the **whale** groups that feed **within** the study area had **not** been studied prior to this **project**, aside from observations of mother-calf pairs that were **widely** distributed in the study area throughout the period when bowheads are present (Ljungblad et al. 1980-85a; LGL and Arctic Sciences 1985). Recent **photogrammetric** data from feeding areas in the Canadian Beaufort Sea show that bowheads sometimes segregate strongly by size, and thus by age and breeding status (Davis et al. 1983, 1986a,b). It is important to know whether **a** disproportionate number of the **bowheads** feeding in the study area are from one segment of the population. Information about **the** composition of the whales utilizing the study area is **also** important **in** assessing the food requirements of bowheads feeding **there**. Food requirements differ considerably according to **whale** size and breeding status (see 'Energetic of **Bowheads**' section, beyond).
4. Residence times (**and turnover**) of individual whales in specific feeding locations within the Eastern Alaskan study area were unknown prior to this study. For example, the study area might be used by a rather **low** number of bowheads that feed there for prolonged **periods**, or by **larger** numbers of bowheads **that** each feed there for **only** a brief period. In the former case, the study area might **be** a feeding

area for only a few whales, but might provide a significant fraction of the **annual** food **supply** for those few individuals. In the latter case, the study area would be less important as a feeding area for any one individual.

5. Stomachs of several whales taken near **Kaktovik** during the autumn hunt contained mainly **copepods** and **euphausiids** (Lowry and Frost 1984). However, prior to this study little was known about where in the study area or water **column** these prey are taken. For whales within the study area, the amounts of time devoted to skim-feeding at the surface, near-bottom **feeding**, and water column feeding had **not** been documented. The numbers and durations of feeding dives of each type were unknown, as was the volume of water filtered during an average dive or an average day.

### Objectives and Approach

To determine the extent and nature of utilization of the study area by feeding bowheads, it is necessary to determine how many bowheads are present at various times in the late summer-early autumn period. It **is** also necessary to determine the activities of these whales, including the proportion that are feeding and the nature of feeding (**e.g.** near-surface, water column, near bottom).

As part **of the** 1985-86 study of **bowheads** in the Eastern Alaskan **Beaufort** Sea, we conducted **aerial** surveys to determine the seasonal distribution of **bowheads** in 'the study area, including their distribution relative to oceanographic factors and food availability. (Previous sections of this report document the results concerning water mass distributions and **zooplankton** availability.) We **also** obtained aerial observations of bowhead behavior to evaluate the proportion of the **whales** that were feeding, feeding **modes**, and other aspects of behavior. Data on the durations of surface-dive cycles were acquired to assist in deriving a correction factor for submerged **whales** missed during aerial surveys. Calibrated vertical photography was used to determine **the** sizes of the whales utilizing various parts of the study area. Because many bowheads are individually recognizable from natural markings, the **photogrammetry** program also provided refighting data. This helped to determine whether specific individuals lingered in certain preferred feeding areas, and whether they returned to the same feeding areas in successive **years**. We **also** radio-tagged **bowheads** in an attempt to provide additional data on feeding behavior and residence times in feeding areas.

### Methods

**All** aircraft work was done using a **DHC-6-300** Twin Otter aircraft, which was based at **Kaktovik** from 4 **September** to 3 October 1985, and from 2' to 27 September 1986. The Twin Otter is a high-wing aircraft powered by two turboprop engines. The aircraft was equipped with wingtip fuel tanks for extended endurance, a **GNS** 500A Very Low Frequency navigation system, a radar altimeter, **an** inverter for 120 v/60 Hz power, three bubble windows (right center, left center, left rear), and a ventral camera port. During the first **half** of September in both years, airborne remote sensing equipment was also aboard the aircraft (see 'Water Masses' section, p. 30-34).

## Systematic and Reconnaissance Surveys

Systematic Aerial Surveys. --During September of 1985 and 1986, we **attempted** to conduct weekly surveys of the southern 2/3 of the study area (**from the shore or barrier islands north** to the 2000 m depth contour). Because previous observations of feeding **whales** within the study area were **in** water <200 m deep, more effort was devoted to the 0-2.00 m depth stratum (continental **shelf** zone) than to the 200-2000 m stratum (continental slope zone). A series of transects was established within each of these two strata.

Transect positions were randomized and **transects** were oriented **roughly** perpendicular to the depth contours **to ensure that density** estimates **would be** unbiased (Eberhardt 1978; Anderson et al. 1979). The shelf zone was divided into 12 strips 10.6 km wide (**plus** a triangular 13th strip). The slope zone was divided into eight strips 18.5 km wide. Within each strip, a transect was selected at random (Fig. 110). The 13 'continental shelf' transects **totalled** 832 km in length; the eight 'continental slope' **transects** tot.ailed 428 km.

In 1985, systematic surveys of the shelf area were completed four times, on 5-6, **12-13**, 18 and 25-27 September. Fog precluded a survey of the continental slope on or near 5-6 September, but it was surveyed on **12, 19-21**, and **27** September. In 1986, the shelf and slope zones were each surveyed three times, on 4-5, **11-15** and 22-26 September.

Surveys of these transects were at an airspeed of **about** 200 km/h. Survey altitude was normally 305 m above sea **level**, but in 1985 some surveys were at **153 m a.s.l.** when the **cloud** ceiling was **below** 305 m. **On the right** side of the **aircraft**, two observers were always present, one in the co-pilot's seat and another adjacent to a bubble window two seats farther back. "On the **left** side, one observer was adjacent **to** a bubble window two seats behind the pilot, and another observer was sometimes present **in** a rear **seat**. For each **bowhead** sighting, the position, time, number of whales, presence of calves, **heading**, estimated **speed**, and lateral distance from the **flight line** were dictated into **tape** recorders. Lateral distances were measured with **Suunto** inclinometers when the whale's position was 90° to the **left** or right of the **flight track**.

Because few bowheads were detected during systematic surveys, especially in 1985, line transect methodology **could** not be applied to estimate **bowhead** densities. Instead, we used strip-transect methods. Based on the results of Davis et al. (1982), we defined on-transect sightings to be those at lateral distances 200-1200 m when survey altitude was 305 m, and at 100-1100 m when survey altitude was 153 m. **Thus**, transect width was **1 km** on each side of the aircraft, or 2 km in total. The 200 m or 400 m **strip** directly **below** the **aircraft** was considered to be off-transects since **sightability** is reduced in this zone even when observations are through **bubble** windows.

The two right-side observers **usually** observed independently; **their** sightings were not announced **to** other observers. This was done **to** develop a correction factor for missed **whales**, based on the method of Magnusson et al. (1978) as applied to bowheads by Davis et al. (1982). This calculation is based **on** the number of **whales** that are sighted by only one observer vs. the number seen by both observers. Because there was a bulkhead between the two right-side observers, neither observer received any visual cues indicating

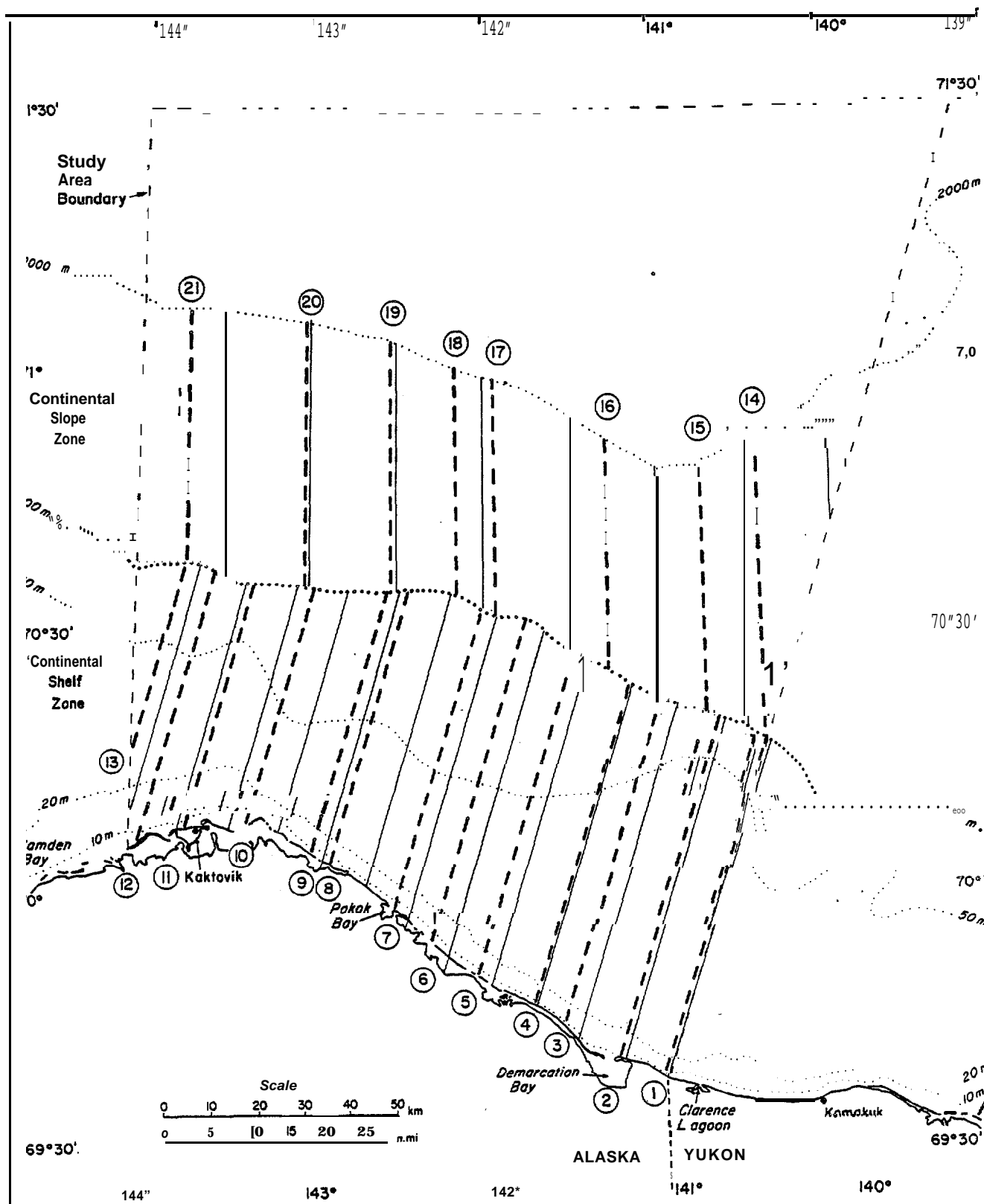


FIGURE 110. Locations of 21 aerial survey transects (dashed lines) within the study area. For each strip demarcated by continuous lines, one transect was selected at a random location (see text).



that the other observer had seen a bowhead. When a bowhead was seen on the right side of the aircraft, it was not possible to circle to obtain more detailed observations, since this would have required notifying the other right-side observer that a bowhead had been seen. However, when a bowhead was seen by observers on the left side, the sighting was announced and the aircraft circled, usually once. Additional sightings (or confirmatory data) acquired during these brief periods of circling were included in density calculations.

Reconnaissance Surveys. --In addition to near-weekly systematic surveys of the slope and shelf strata, we conducted numerous reconnaissance surveys in these areas from 5 September to 3 October 1985 and 3-27 September 1986. The reconnaissance was done while we searched for whales for purposes of behavioral observations, photogrammetry, and radio-tagging. Most bowhead sightings during this project were obtained during the reconnaissance flights, which were concentrated in areas where the probability of whale sightings was highest. All flight lines and sightings are mapped below.

While the boat chartered for zooplankton studies was moving along its transects during the 4-18 September 1985 and 3-19 September 1986 periods (see 'Zooplankton and Hydroacoustics' section, p. 141-143), an observer maintained a watch for bowheads whenever visibility was adequate. Similarly, observers aboard the smaller boat used for the 1986 radio-telemetry program (see below) watched for bowheads. No bowheads were seen along the boat transects in 1985. Numerous bowheads were seen from both boats in 1986. However, all 1986 sightings were in areas where aerial observers also detected bowheads. Thus, the boat-based sightings are rarely mentioned here.

Supplementary Survey Coverage by Other Projects .--Several other studies of bowhead whales in the Canadian and Alaskan Beaufort Sea were conducted during the late summer and autumn of 1985 and 1986. Most of these studies included aerial survey coverage of parts of our study area, in some cases including periods before or after our field seasons. We mapped the results from these other studies to supplement our own data.

In both 1985 and 1986, the Naval Ocean Systems Center (NOSC) conducted extensive surveys of the Alaskan Beaufort Sea for MMS. Their surveys provided some coverage of deep waters north of the area surveyed by us, plus some additional coverage of the areas where we worked. NOSC also obtained some coverage of our study area in August and October, before and after our study periods. Our 'supplementary coverage' maps show all of the NOSC flight lines and bowhead sightings within the mapped area (approx. 139°W to 145°W) during the 1 August to 20 October periods of 1985 and 1986. The 1985 NOSC data are from Ljungblad et al. (1986c, Appendices A and C). The 1986 NOSC data are from pre-publication copies of their flight line and sighting maps (J. Clarke and D. Ljungblad, pers. comm.).

Several industry-funded studies of bowheads were conducted by LGL in 1985-86, mainly in areas east or west of our study area. However, these studies provided additional aerial reconnaissance of parts of our study area. In 1985, these studies included the following:

1. **Photogrammetric** flights near the east edge of our study area, **14 Aug-8 Sept 1985** (four flights into the area that we mapped; Davis et al. **1986b**) .
2. Reconnaissance flights in October 1985, including nine flights into 'our' area by Evans and **Holdsworth** (1986) and one by Johnson et al. **(1986)**.
3. Systematic surveys near the west edge of our official **study** area, **5 Sept-20 Ott 1985** (21 flights into the area that we mapped; **McLaren** et al. 1986).

For each of these studies, flight lines and sightings within the area considered in this report are shown on our 'supplementary coverage' maps and are taken into account in our description of the seasonal occurrence of bowheads in the Eastern Alaskan Beaufort Sea during 1985.

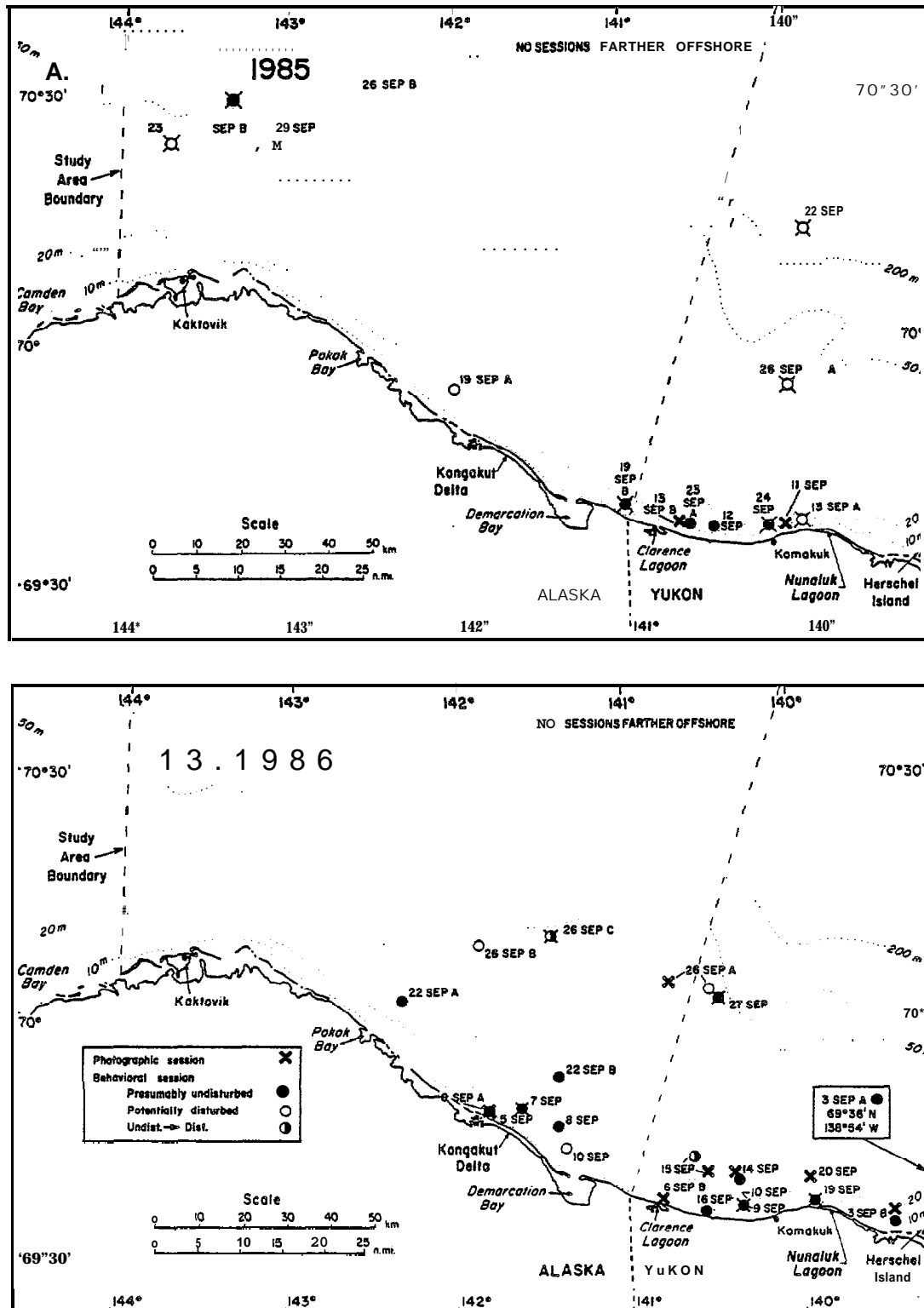
Similarly, for much of September 1986, LGL conducted near-daily aerial surveys and other observations around the Corona drillsite north of Camden Bay (Evans et al. in prep.; **Koski** and Johnson in prep.). Their work overlapped the western edge of our study area. Their flight lines and sightings within our study area are included on the 'supplementary coverage' maps in this **report**.

Systematic aerial surveys of the Canadian Beaufort Sea were conducted in" late August and early September of 1985 (Norton and **Harwood** 1986) and 1986. (**Harwood** and Norton 1986; ESL **unpubl.** data). Their survey coverage and bowhead sightings west of Herschel Island are mapped here.

### Behavioral Observations

On 11 occasions in 1985 and 17 occasions in 1986, we used **the** aerial observation procedures described by Richardson et al. (**1985b**) to observe **the** behavior of bowheads (Fig. 111). Four observers in the Twin Otter aircraft circled high above the whales. Aircraft altitude was 457 m or (on **13 Sept 1985**) 610 m, either of which is high enough to avoid significant aircraft disturbance (Richardson et al. **1985b**). Airspeed during circling was 155 km/h.

The 28 behavioral observation sessions ranged from 0.2 to 2.8 h in duration, and **totalled** 32.5 h (15.2 h in **1985** and 17.3 h in 1986). **In 1985**, five sessions were within the 'official' study area, as outlined by the dashed lines on Fig. 111A. Two sessions were slightly to the east and **well** offshore. Four sessions were slightly to the east and within 3 km of shore near Komakuk (Fig. 111A). In 1986, eight sessions were within the official study area, **two** were slightly to the east and well offshore, and seven were to the east and within 10 km of shore (Fig. **111B**). In analyses of behavior within the official study area, we included the offshore sessions just east of the study area, since sea conditions, ice, and whale activities there seemed similar to those farther west within the official study area. However, we often treated the nearshore sessions east of the official study area separately. Water depths at observation locations were usually about 5-50 m, but in 1985 the depth was 280 m at one location. Sea states were 0-3 but usually 1-2. In 1985, ice cover at the 11 observation sites ranged from 0 to 100% grease ice, and from 0 to **65%** thicker ice. In 1986, there was no ice near any observation site.



**FIGURE 111.** Locations where behavior of bowheads was observed, and where calibrated vertical photographs were acquired, September 1985-86. When there was >1 behavioral or photo session on one date, the sessions are designated A, B and C (see Tables 40, 43, 44, beyond).

Throughout each observation session, two observers on the **right** side of the aircraft dictated behavioral observations into a tape recorder, and a third observer on the right side operated a video camera whenever whales were at the surface. The fourth observer, on the left side, watched for whales 'outside' the area being circled and operated **sonobuoy** receiving equipment (see below). During each surface/dive sequence, we recorded the same behavioral variables as in our previous behavioral studies (Würsig et al. 1984, 1985a; Richardson et al. 1985b). In addition, we estimated the net distance **travelled** during dives, i.e. the distance between the location where an identifiable individual dove and the location where it next surfaced.

Behavioral data were transcribed from audiotape between flights, and the videotape was examined for details not noted during the real-time behavioral **dictation**. The combined data were coded numerically as in our previous work. These records were hand checked, and then entered into an Apple **II+** microcomputer for computerized validation and analysis. In total, 679 surfacing and 69 dive records were obtained during this study. Of these, 472 "and 33 were obtained under 'presumably undisturbed' conditions. Of the remaining 'potentially disturbed' records (207 surfacings and .36 dives), most were obtained in the presence of noise from distant seismic vessels. Because surfacing, respiration and diving behavior of bowhead calves (<1 yr **old**) is considerably different than 'that of older 'non-calves' (Würsig et al. 1984, 1985a), most of our behavioral analyses exclude our few data from calves.

#### Measurements of Underwater Noise .

During **most** behavioral observation sessions, underwater sounds near the whales were monitored by **sonobuoys** (AN/SSQ-57A or AN/SSQ-41B, Sparton Electronics). Hydrophore depth was either 18 m or 9 m. **Sonobuoys** with a 9 m depth setting were specially manufactured for our use in water shallower than 18 m. **Sonobuoy** signals were received and recorded aboard the aircraft via calibrated equipment (Greene 1985).

Industrial sounds audible on the **sonobuoy** recordings were analyzed by Greeneridge Sciences Inc. using their standard analysis methods for these types of sounds (Greene 1985). Three types of results were derived:

1. Power spectrum graphs showing spectrum **levels** vs. frequency, along with levels in various standard bands. For frequencies up to 1000 Hz, each power spectrum analysis was based on about 8 s of digitized sound data in 1985, and about 30 s of data in 1986.
2. Waveforms and peak **levels** for pulses from distant seismic survey vessels.
- 3\* Waterfall graphs showing the rapid changes in frequency content of seismic pulses.

No specific analysis of the bowhead calls audible on the **sonobuoy** tapes was. needed for our purposes. However, we did note the occasions when **calls** were and were not detected.

Radio Telemetry\*

Radio tagging was planned for two primary purposes: (a) to determine how long **whales** remain in a feeding **area**, and (b) to provide behavioral data on **surfacing/dive** sequences and small-scale movements **within** feeding areas, including data **on** behavior **at night**. The tags might also provide data on **longer** distance movement patterns, although this was not a primary objective. J. Goodyear provided two types **of** small radio tags that are deployed onto whales **by** crossbow from distances up to 25 m.

The primary type of tag was a small (**about 7 x 1½** cm) custom-built '**capsule**' tag that penetrates no more than 9 cm **into the** blubber, leaving only a fine wire antenna (1 mm x 45 cm) protruding from the surface. The electronic components consisted of a 148.00-149.00 MHz telemetry transmitter with high-impact crystal and power output 4 or 12 mW (L. & L. Electronics or Telonics, respectively). Four small backward-angled blades were mounted **to the front** of the tag to aid in penetration. Six tines protruded laterally near the **front end** of the capsule, and were angled backward **to hold** the tag within the blubber. Maximum attachment time has not been tested, but up to several weeks or possibly months is expected. Battery lifetime is several weeks. Capsule tags have been tested **on** gray whales (Swartz et al. 1986) and, less extensively, on fin whales (Goodyear et al. 1985). The main advantages of the capsule tag are (a) its **small** size, (b) its relatively **long** lifetime, and (c) the fact that the antenna is the only part that remains external to the surface of the **whale**. The **small** size of the tag was an important consideration in obtaining **local** community approval of the project. Point (c) was expected to be **an** important advantage with bowheads, which often move amidst ice.

For backup purposes, we were prepared **to** use Goodyear's well-tested '**remora**' tags (Goodyear 1981, 1983; Goodyear et al. 1985). However, remora tags were in fact **not** used, and are not discussed further,

In early-mid September 1985, J. Goodyear was aboard the '**Annika Marie**', a 13-m boat, while it conducted **zooplankton** and physical sampling in the official study area (see '**Zooplankton and Hydroacoustics**' section). However, **whales** were virtually absent from the official study area **at that time**, and there were no good tagging opportunities in 1985.

In September 1986, a smaller boat, an 8-m Munson, was made available by MMS specifically for radio telemetry work. Although there were considerable **logistical** problems, bowheads were accessible **in 1986**, and five bowheads were tagged **during this project**. **Three whales** were tagged from a 2-man sea kayak and two from an outboard-powered Zodiac, both **of** which were deployed from the Munson. Methodological details are given in Appendix 4. In addition, two capsule tags were deployed **in the same area** by B.R. Mate of Oregon State University (**pers. comm.**; see Appendix 4).

We were equipped to monitor the radio tags from a **boat**, aircraft and shore. Boats ('**Annika Marie**' in 1985; Munson in 1986) were equipped with a manually rotatable Yagi-Uda antenna system. The bearings **of** whales (relative

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\* Prepared with assistance from J. Goodyear; Appendix 4 gives details.

to boat heading) were determined using a compass wheel mounted on the pole holding the antenna. Similar equipment was used from shore in 1986. In both years, the project aircraft was equipped with two 3-element **Yagi-Uda** antennae for detection and tracking purposes. **Telonics TR-2** receivers were used. Tests showed that detection range was a few kilometers when the antenna and receiver were in a small boat or on a shoreline near sea level, but at least 30-60 km for a receiver in the aircraft at altitude 900 m (see Appendix 4).

In addition to the primary project aircraft, several other aircraft involved in different bowhead studies off northern **Alaska** were equipped to monitor any tagged whales in both 1985 and 1986. However, no aircraft other than our project aircraft detected any of the **whales** that we tagged.

### Photogrammetry

We photographed bowhead whales using **LGL's** calibrated vertical photography technique (Davis et al. 1983). There were two objectives:

1. To **re-identify** individually recognizable whales and thereby obtain data on their residence times in feeding areas and their movements between locations. The between-day refighting data presented here include sightings in this project of whales photographed during **LGL's** other photogrammetry projects, as **well** as whales that were sighted more than once during this project.
- 2\* To obtain measurements of the sizes of whales in different parts of the **study** area.

Field Procedures.--In 1985, vertical photographs were obtained at the end of 8 of the 11 behavioral observation sessions and on two other occasions (Fig. 111A). In 1986, photos were obtained after 9 of 17 behavioral sessions, and on four other occasions (**Fig. 111B**). During behavioral observation sessions, the aircraft circled at altitude 457 m or more. At the end of 17 of those 28 sessions, the aircraft descended to **lower** altitude and attempted to photograph the whales that had just been observed. During photo sessions, the aircraft flew back and forth above the group of whales at an altitude of about 145 m, attempting to pass directly over **whales** when they were at the surface. Photographs were taken with a hand-held **Pentax** 6x7 cm camera with 105 mm **f2.4** lens pointed vertically downward through a camera port in the floor of the aircraft. The majority of the photographs in 1985 and all of those in 1986 were on Ektachrome 200 **color film**. When lighting was poor during 1985 (i.e. under heavy overcast or late in the day), we often used **Ilford XPl** black and white negative film pushed to ASA 1600 and exposed through a **yellow** filter. Shutter speed was **1/500** s. As each photograph was taken, the altitude of the aircraft was read from a radar altimeter. Two identical **camera/lens** systems were used; the system used for each **roll** of **film** was recorded. An acoustic **levelling** device designed by J. **Cubbage** was attached to the camera on most occasions in 1986 to warn the photographer when the camera was not pointed vertically.

On two occasions in 1985 and one in 1986, we obtained calibration photographs of a target of measured dimensions. This target was spread out on land in a '+' configuration, with **total** length and width of 20.0 m. During

each calibration session, 5-10 photos of the target were taken with each camera and, in 1985, with each film type.

Measurements. --Images of targets and whales were measured directly from the processed film to the nearest 0.01 mm using a Zeiss binocular dissecting microscope and a stage micrometer. The average of three blind replicate measurements was used to calculate the dimensions of the target or whale using the following equation from Jacobson (1978):

$$\text{Calculated length} = \frac{\text{Altitude} \times \text{Image size}}{\text{Focal length of lens}}$$

The dimensions calculated from the above formula were then corrected for distortion caused by aircraft motion (image elongation and focal plane shutter effects; see Davis et al. 1986b).

Calculated target sizes (corrected as above) were regressed against the known target measurements to give the following regression equations:

1985: Actual length = (calculated length - 0.03) / 0.99513

1986: Actual length = (Calculated length - 0.02) / 0.95841

These equations correct for any systematic biases, e.g. in the altitude values derived from the aircraft's radar altimeter. The equation was used to convert calculated whale lengths to actual lengths. Davis et al. (1986b) provide additional information about the corrections that were made, validation analyses, precision and repeatability.

The quality of the measurements varied from one photograph to another because of the varying postures of the whales and changing sea state and lighting conditions. The repeatability of each measurement was assigned a grade from 1 to 6, following Davis et al. (1986b). A grade 1 measurement was the highest quality measurement.

Individual Identification. --The 10 photographic sessions in 1985 provided a total of 267 images of bowheads, 258 of which were of a quality suitable for printing. The 13 sessions in 1986 provided 305 images of quality suitable for printing. Each whale image was assigned a re-identification grade, as in previous studies (Davis et al. 1983, 1986a,b). Photographs of whales that would be recognizable in another photo of similar or better quality taken in another year were grade A. Photos of whales that would be recognizable in a photo of similar or better quality taken the same day or within a few days were grade B. Photos of whales that probably would be unrecognizable in another photo of similar or better quality were grade C.

The grading of prints involved a subjective assessment of focus, resolution, lighting, glare, reflection, sea state and posture of the whale, as well as distinctiveness of the whale's markings. A poor quality photo of a very distinctively marked whale might be graded A while an excellent photo of a whale with no distinctive markings might be graded C. We have not considered grade C photographs in this analysis.

The within-1985 refighting data presented here are based on **an** analysis of the 212 grade A and B whale images (134 different whales) acquired during the present study, plus a comparison of these images with 1136 grade A and B whale images (753 different whales) obtained by LGL in the Canadian Beaufort Sea on 3 August-14 September 1985 (cf. Davis et al. 1986b). Our 212 images were also compared with 21 whale images (13 different whales) acquired on 19 September-15 October 1985 during a study in the Alaskan Beaufort Sea west of our study area (Johnson et al. 1986). To identify between-year **resightings**, we also compared our 212 grade A and B images with all grade A whale images acquired by LGL in the Canadian Beaufort Sea in 1981, 1982, 1983 and 1984 (cf. Davis et al. 1982, 1983, 1986a,b; Würsig et al. 1985b).

The within-1986 refighting data are based on analysis of 291 grade A and B whale images (223 different whales) obtained during this study in 1986, plus a comparison of these images with 151 grade A and B images (61 whales) obtained in a study conducted primarily west of our study area, but overlapping with it, from 4 September to 3 October 1986 (Koski and Johnson in prep.). To identify between-year **resightings**, we compared our 1986 grade A images (n = 81) with all grade A images acquired by LGL in the Alaskan and Canadian Beaufort Seas in 1981-85 (n = 729).

## Results

### Seasonal Occurrence of Bowheads, Autumn 1985

The results of **aerial** surveys in and near our study area during August-October 1985 are shown in Figures 112-120 and summarized below. We consider survey coverage by all bowhead investigators," not just ourselves.

August 1985.--During August, no bowheads were seen west of the study area, and only four single whales were seen within it. More bowheads were present just east of the study area, both **well** offshore and close to shore between Komakuk and Clarence Lagoon (Fig. 112-113; Davis et al. 1986b; Ljungblad et al. 1986c; Norton and Harwood 1986).

September 1985.--Little surveying was possible during the 1-10 September period because of frequent low cloud. However, it was apparent that few if any bowheads were within the official study area in early **September**. None were seen during our systematic survey of the continental **shelf portion** of the study area on 5-6 September or during NOSC surveys farther offshore (Fig. 114). Survey conditions were relatively good, and there was virtually **no** ice in the areas surveyed. In contrast, very large numbers of bowheads were present east of the study area in southern Mackenzie Bay (138°W) on 6 September (Davis et al. 1986b).

On 11-13 September, we saw only two **bowheads** during a systematic survey of the ice--free continental shelf and **slope** strata (Fig. 115A). Other workers saw none within the official study area, but saw several bowheads farther <sup>west</sup> (Fig. 115B; Ljungblad et al. 1986c; McLaren et al. 1986). Thus, migration of a few bowheads through the study area had apparently begun. However, numbers in and west of the study area were **low** compared with numbers farther east. Many bowheads were near Komakuk, just east of the official study area (Fig. 115). Some of these fed near the surface; they were not traveling strongly



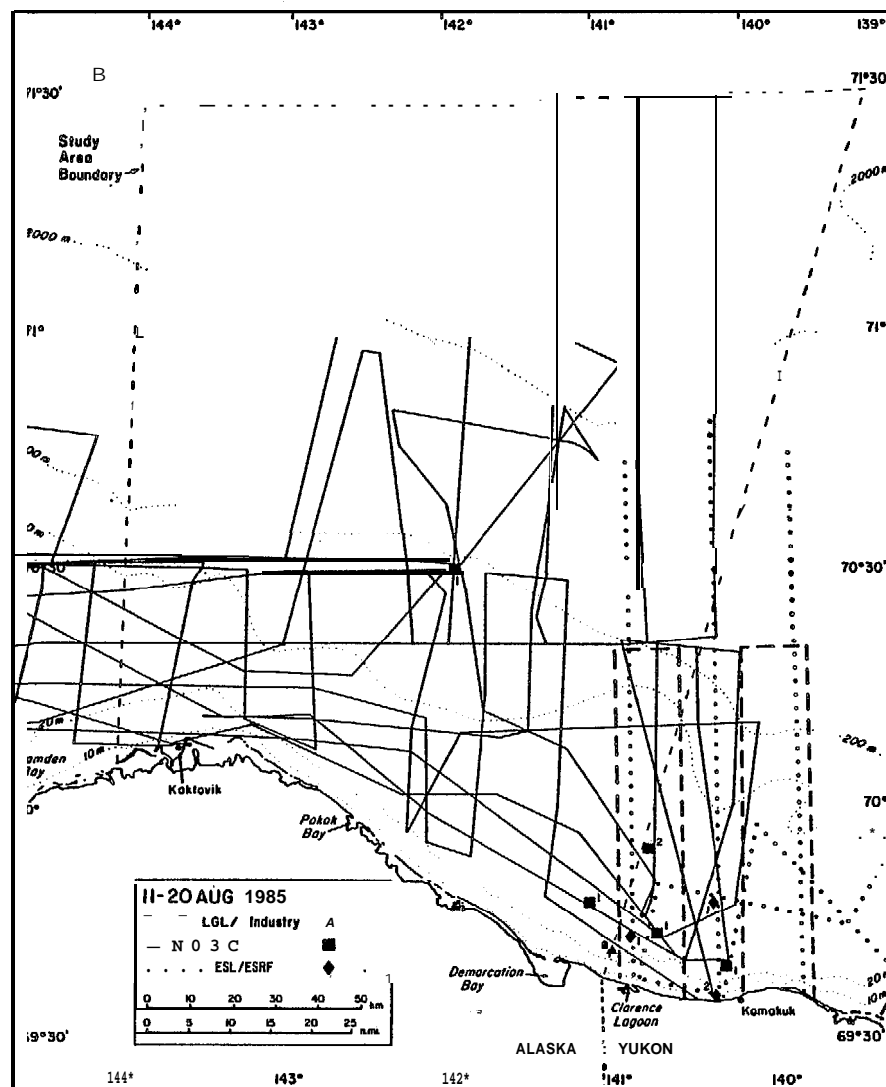
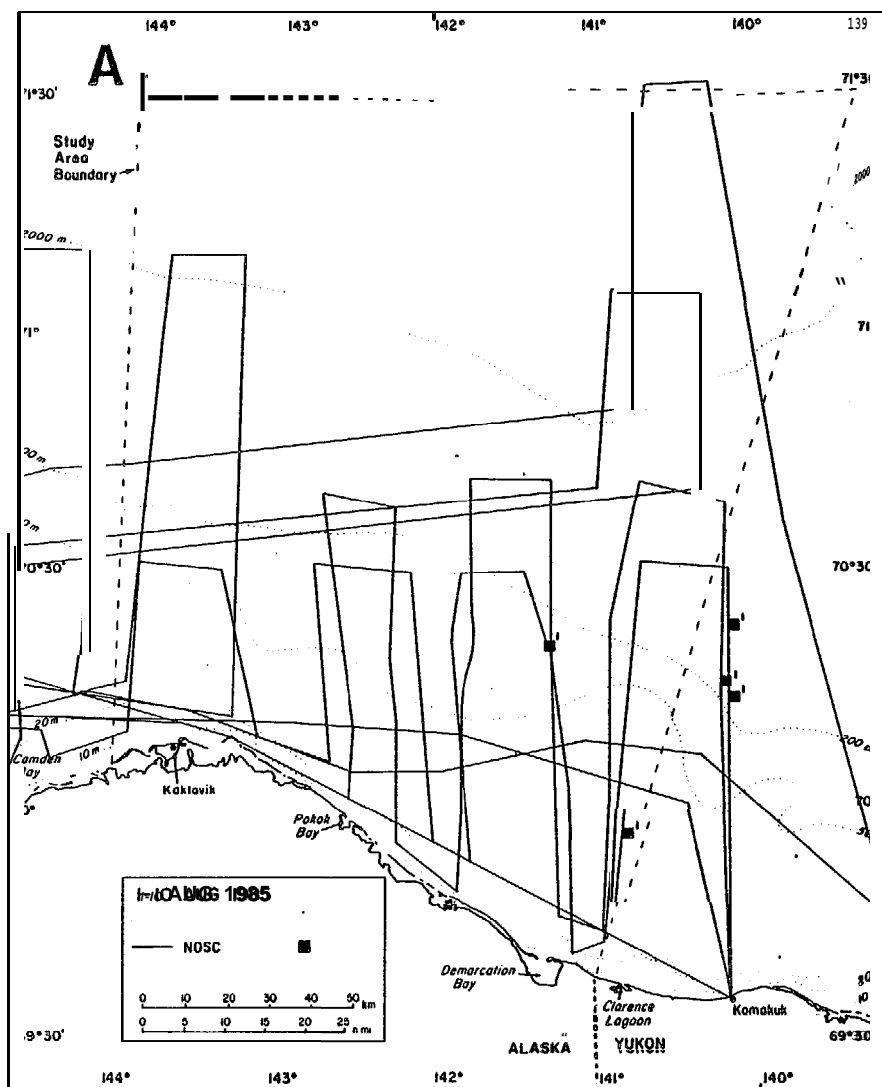


FIGURE 11.2. Aerial survey routes and bowhead sightings during other projects, (A) 1-10 August 1985, and (B) 11-20 August 1985. LGL/Industry, NOSC and ESL/ESRF data are from Davis et al. (1986b), Ljungblad et al. (1986c) and Norton and Harwood (1986), respectively.

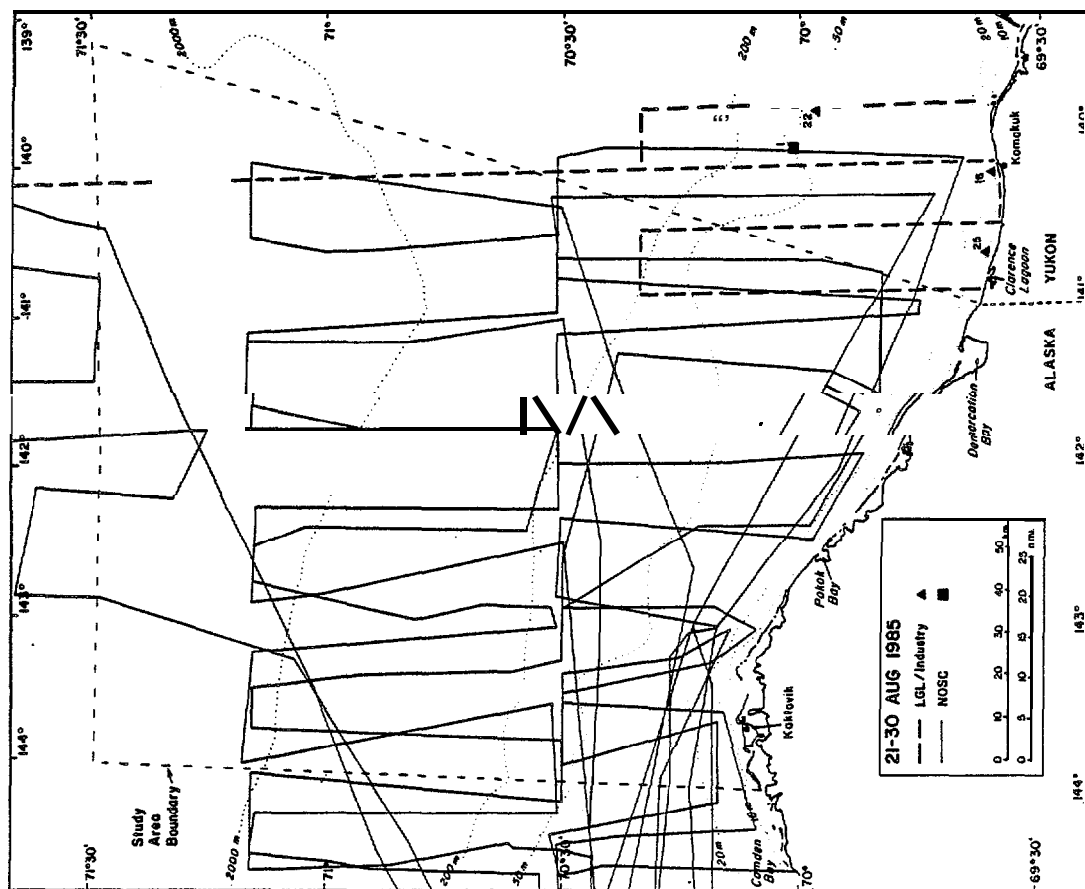


FIGURE 113. Aerial survey routes and bowhead sightings during other projects, 21-30 August 1985. Sources as in Fig. 112. Note: This map shows far-offshore coverage mapped by Ljungblad et al. (1986c, p. A-61) but not included in preliminary NOSC data quoted by Richardson et al. (1986b, p. 159, 172).

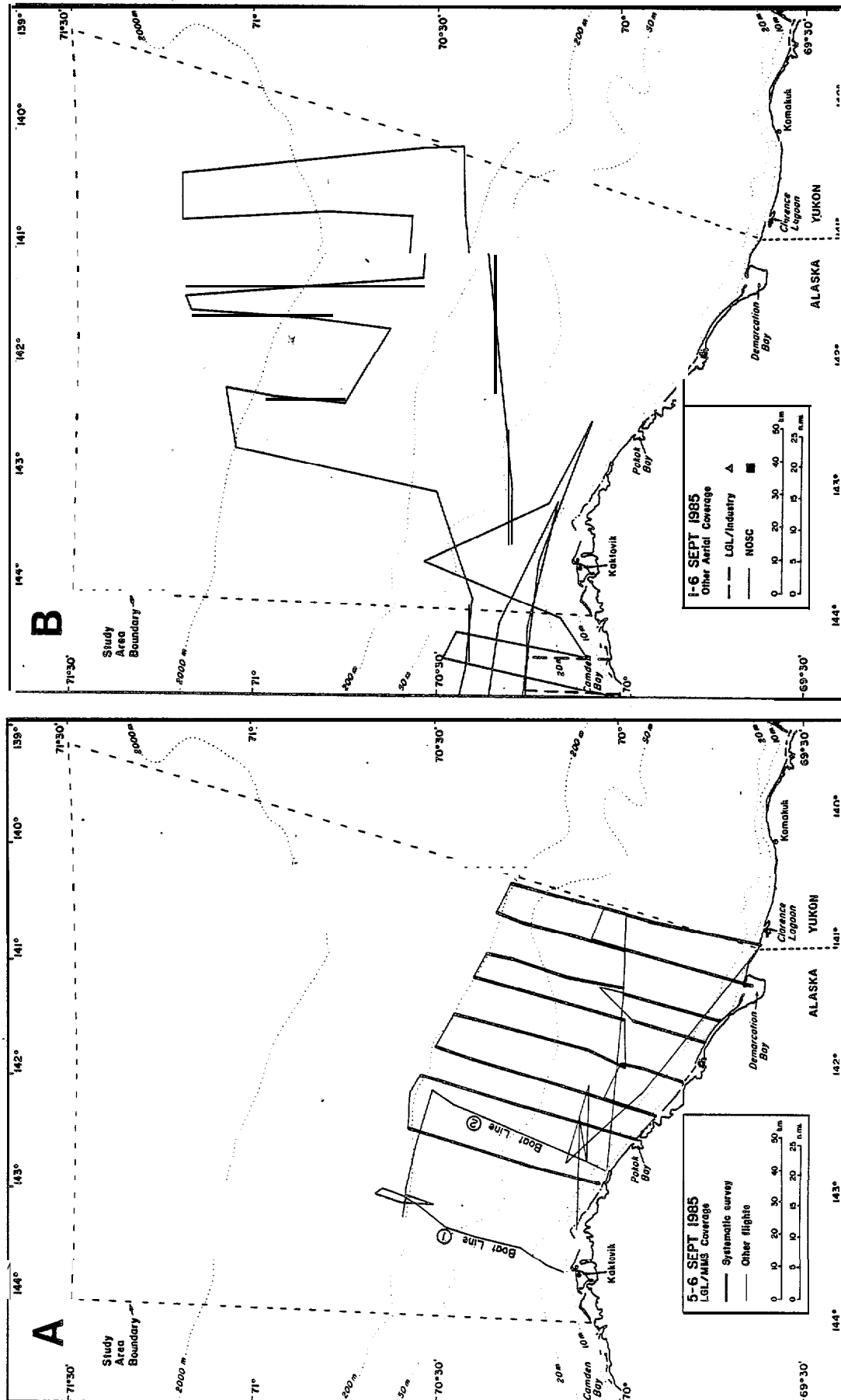


FIGURE 114. Aerial survey routes during (A) this project, and (B) other projects, 1-6 September 1985; no bowheads were seen within the area mapped. Data in (B) are from Ljungblad et al. (1986c) and McLaren et al. (1986).

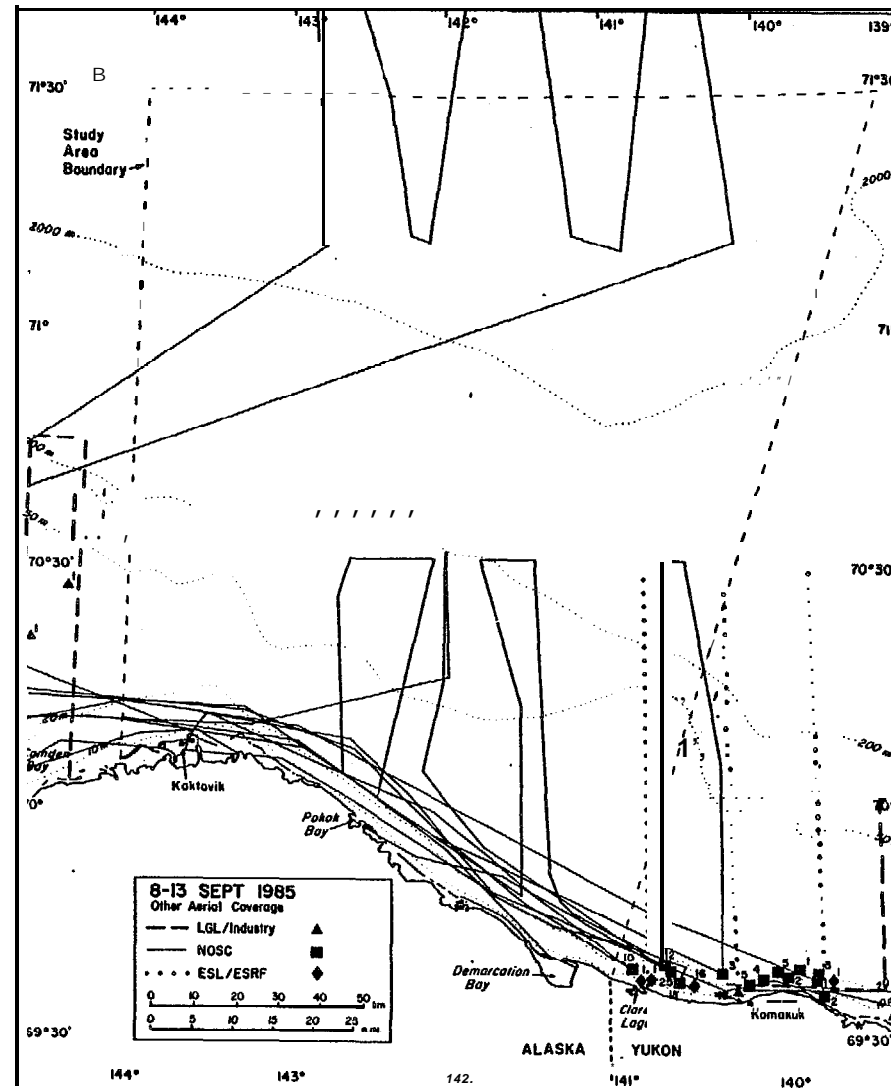
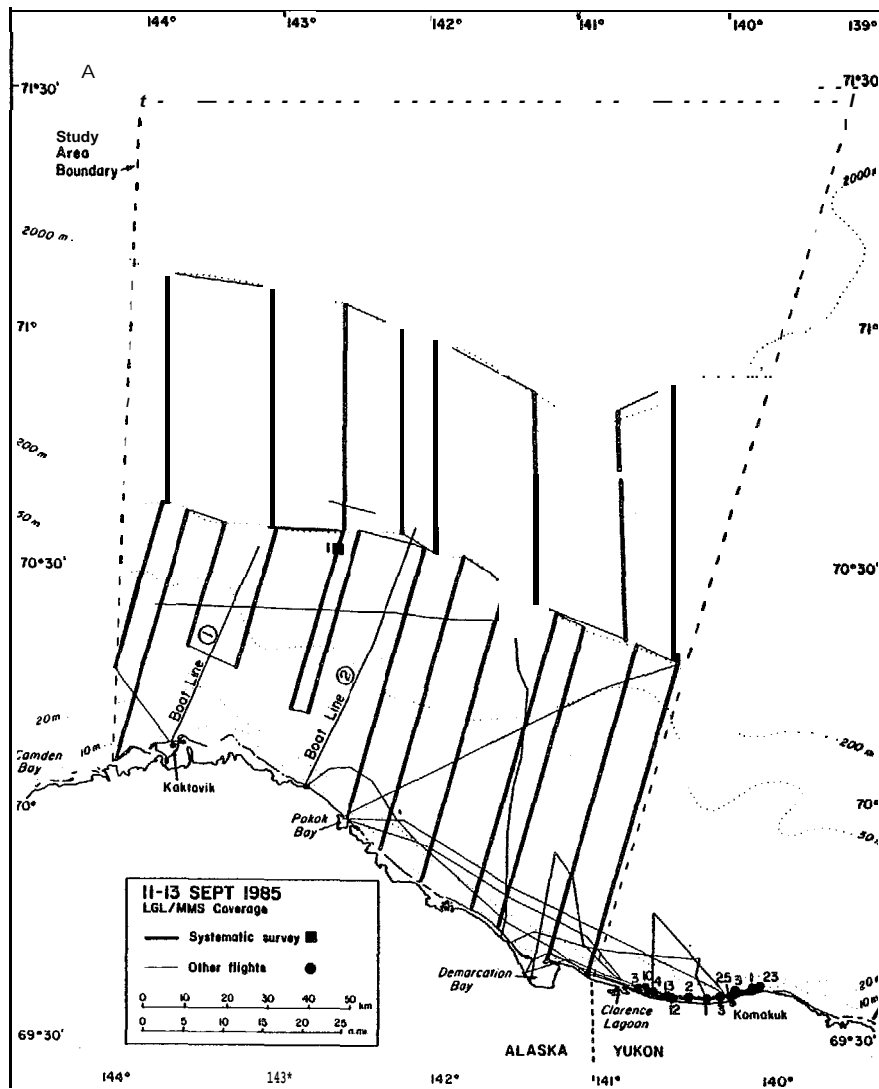


FIGURE 115. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 8-13 September 1985. Sources for (B) as in Fig. 112, 114.

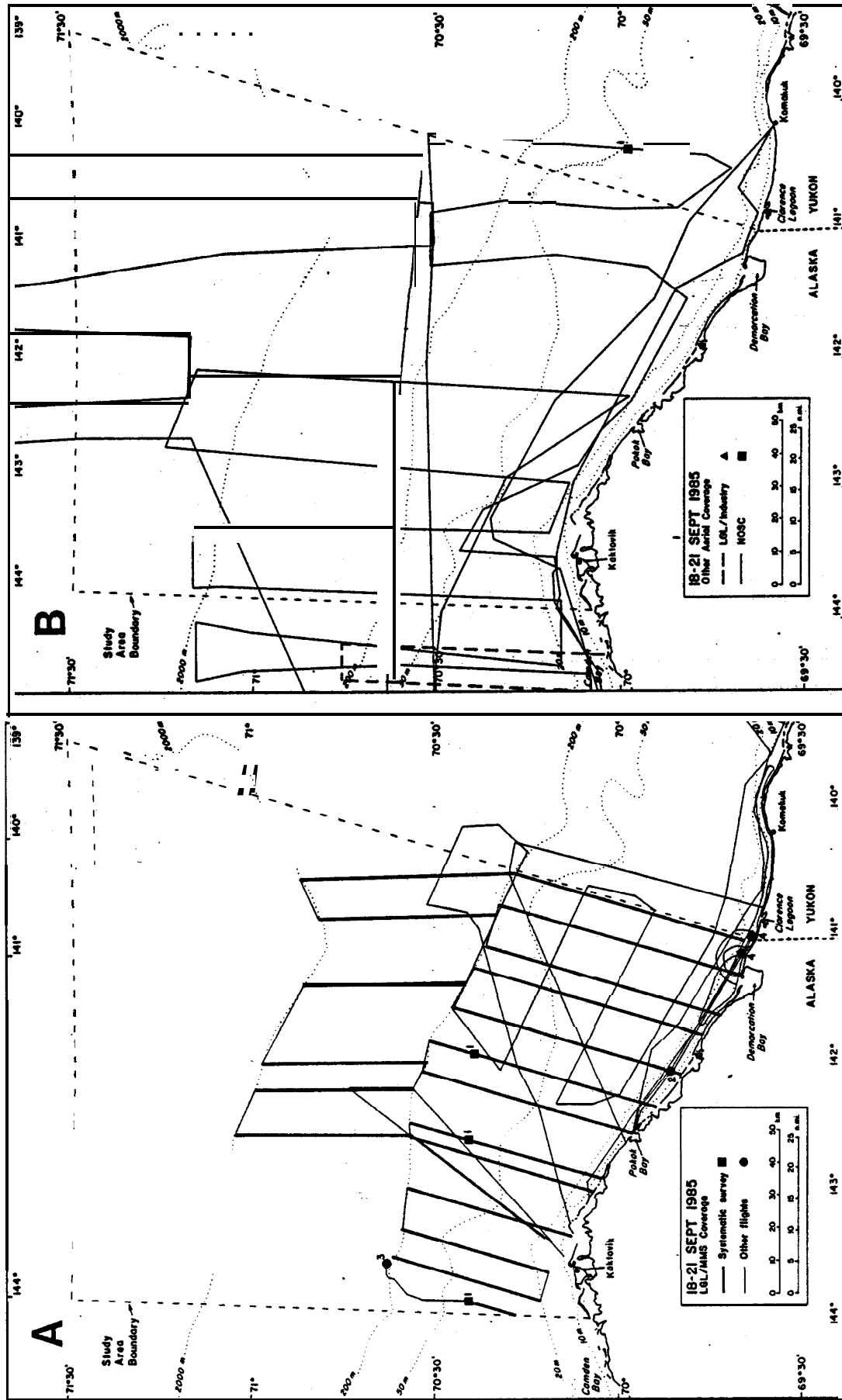


FIGURE 116. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 18-21 September 1985. Sources for (B) as in Fig. 114.

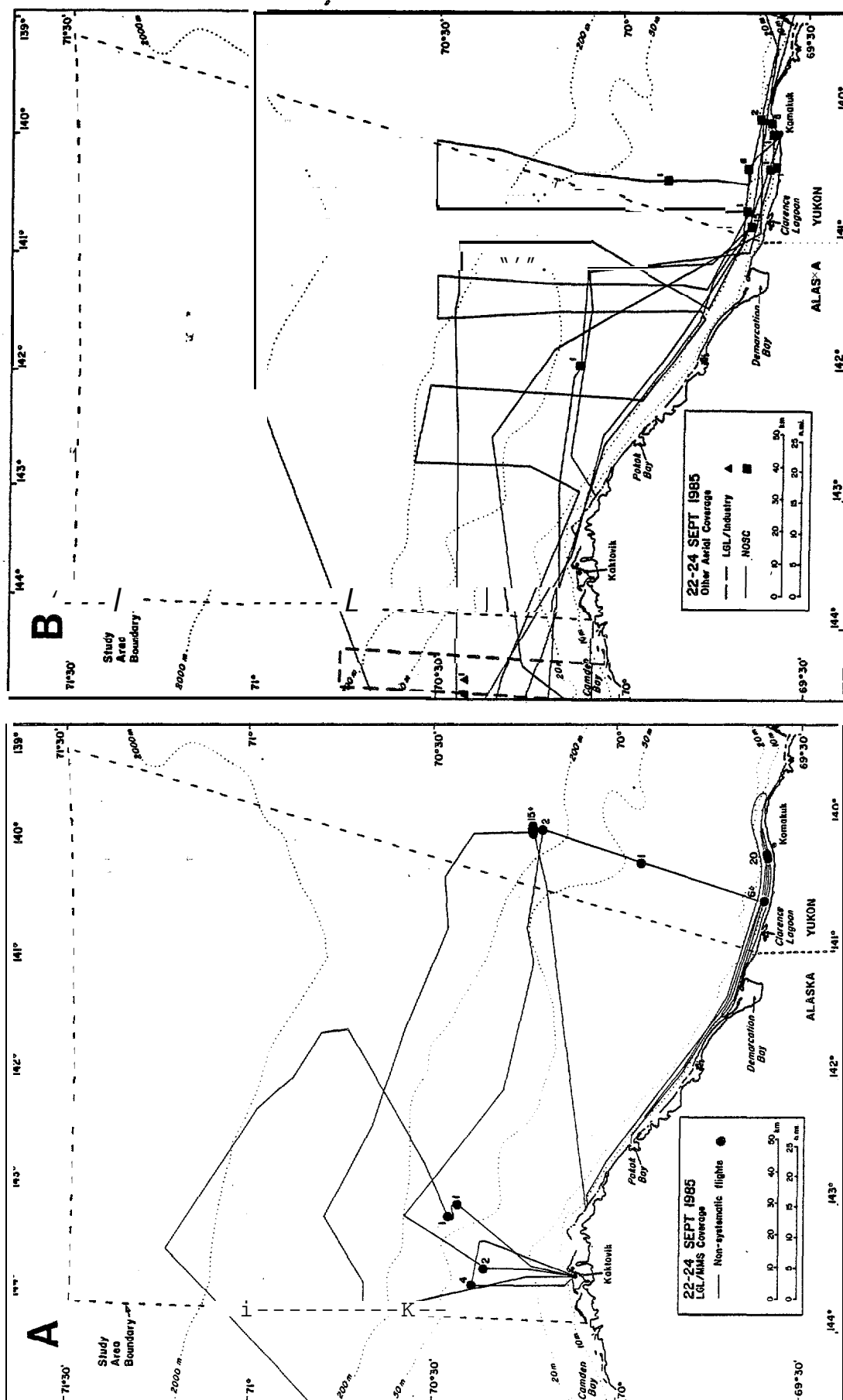


FIGURE 117. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 22-25 September 1985. Sources for (B) as in Fig. 114.

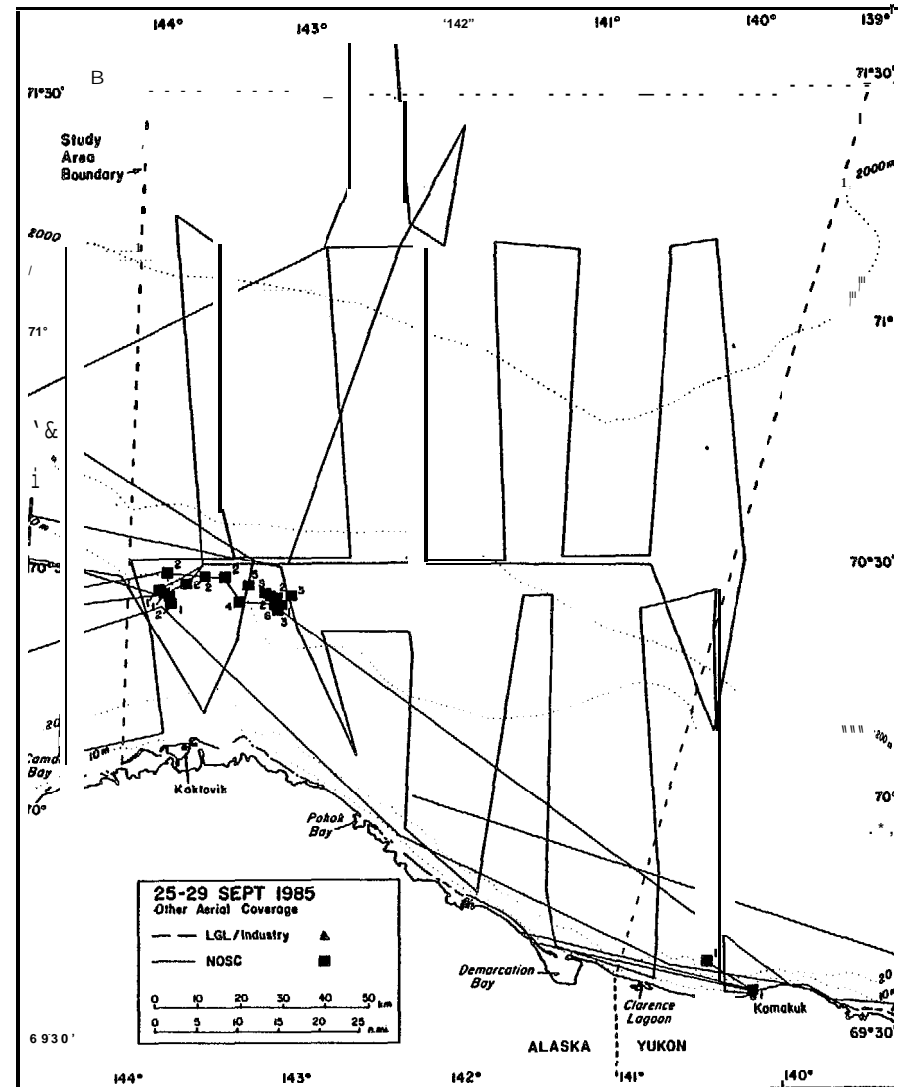
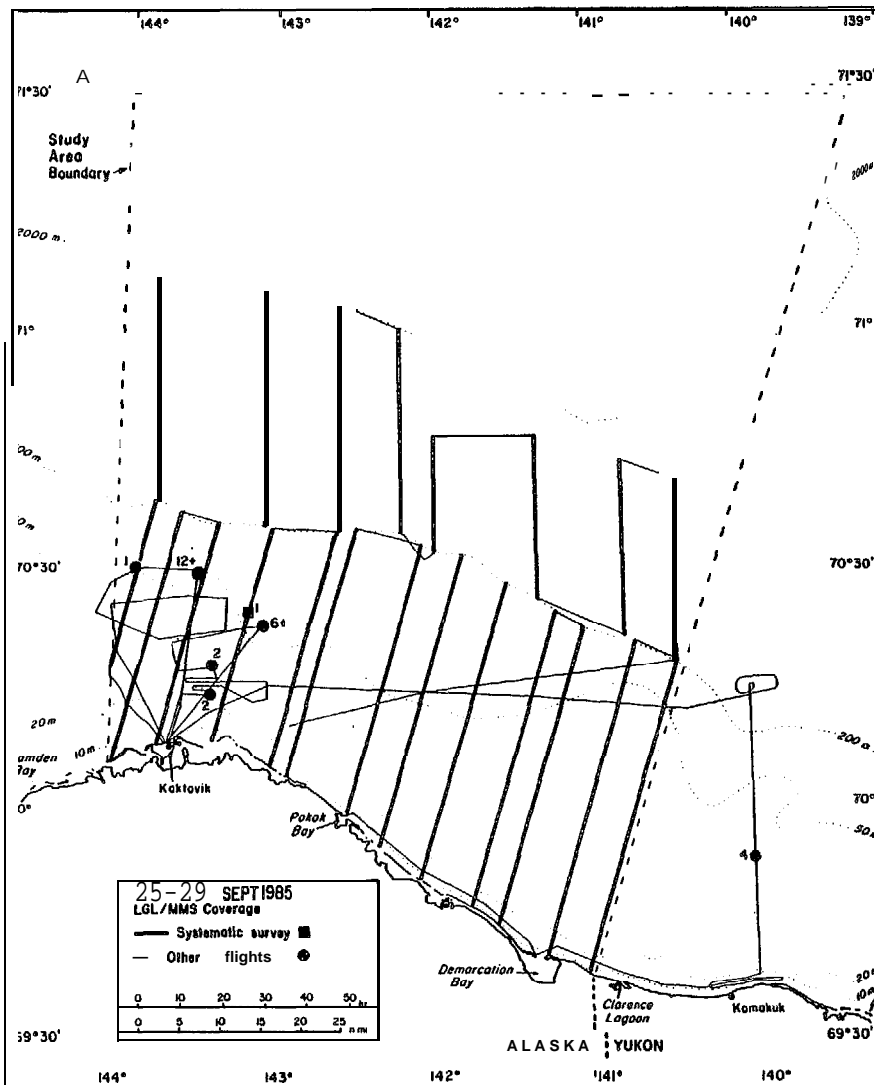


FIGURE 118. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 25-29 September 1985. Sources for (B) as in Fig. 114. Note: the nearshore coverage shown by Ljungblad et al. (1986c, p. C-31) and mapped here differs slightly from that in the preliminary NOSC data quoted by Richardson et al. (1986b, p. 166B).

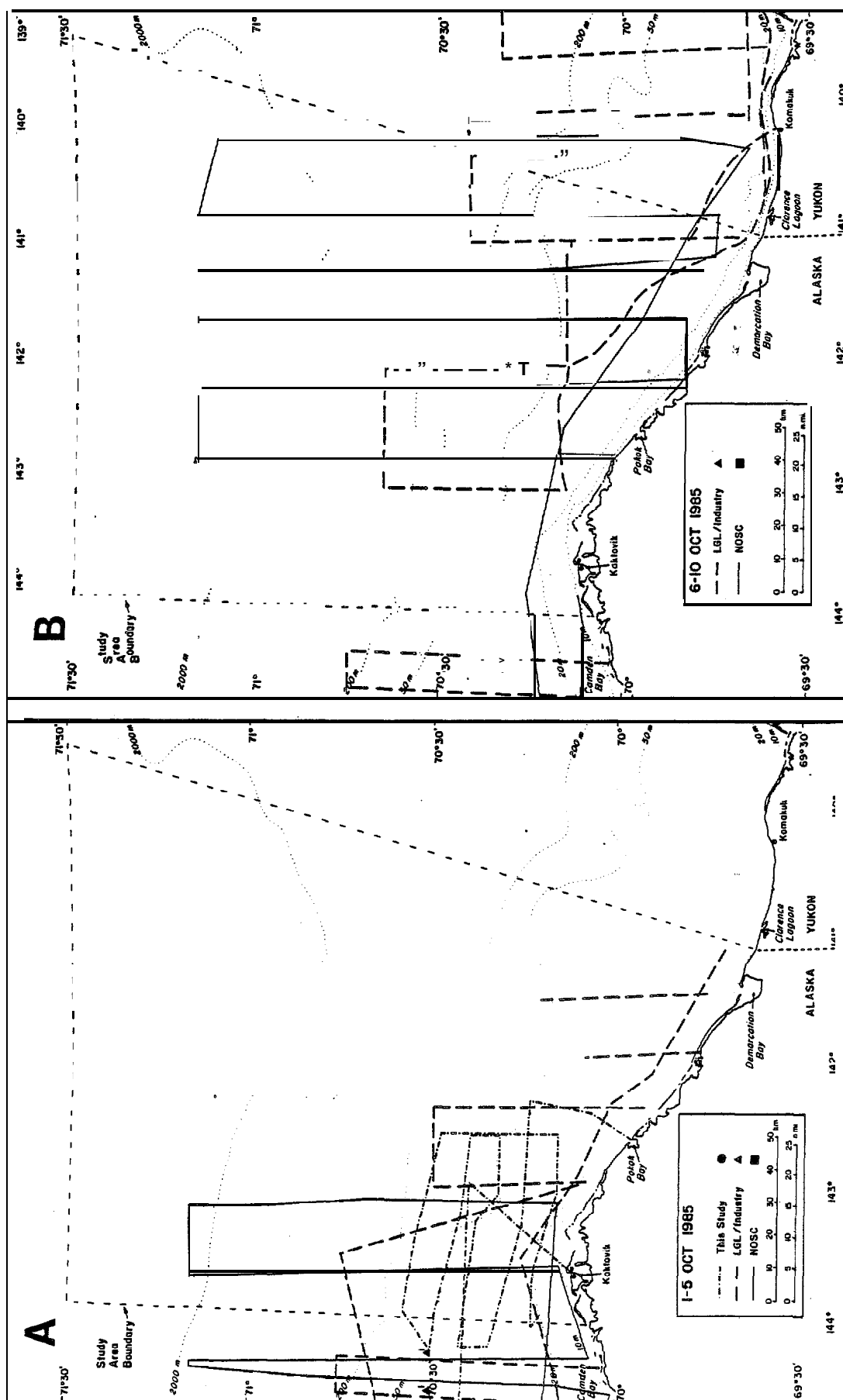


FIGURE 119. Aerial survey routes and bowhead sightings during (A) 1-5 October 1985, all projects, and (B) 6-10 October 1985, other projects. Sources are this study, Evans and Moldsworth (1986), Johnson et al. (1986), Ljungblad et al. (1986c) and McLaren et al. (1986).



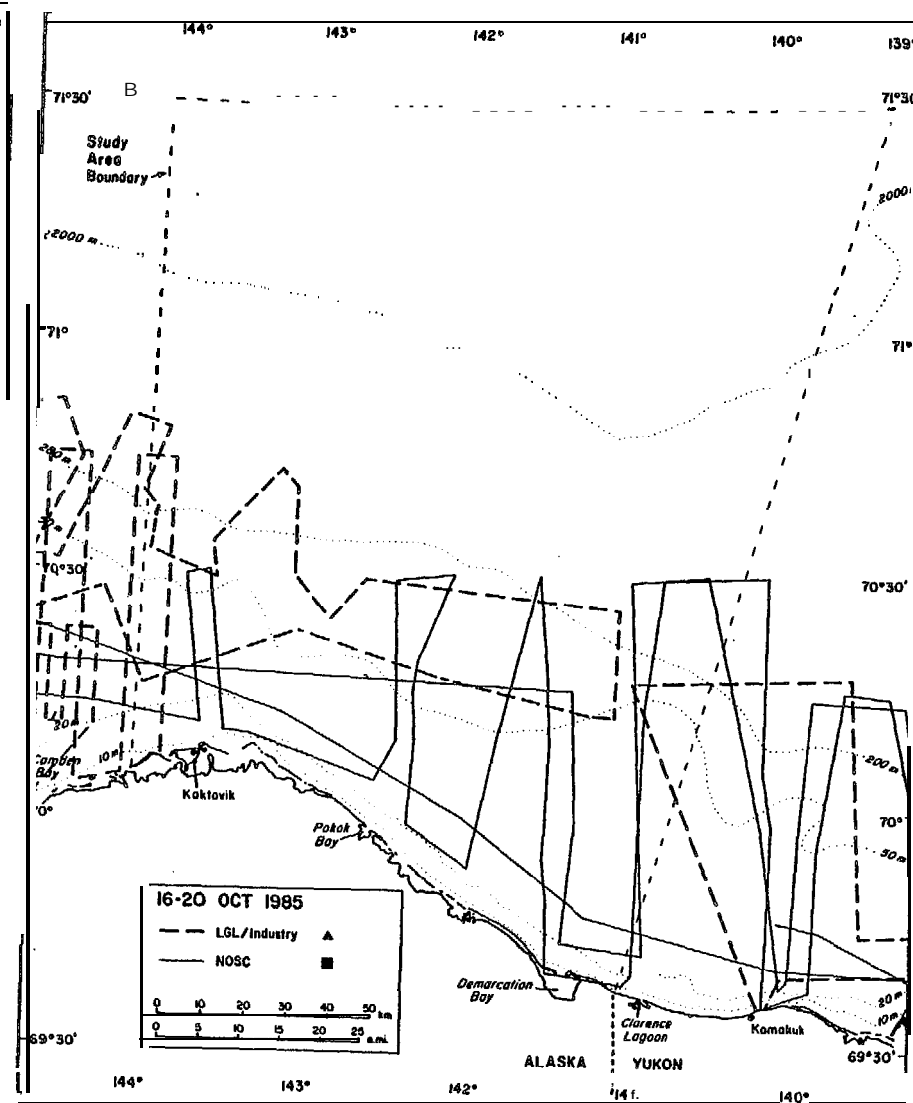
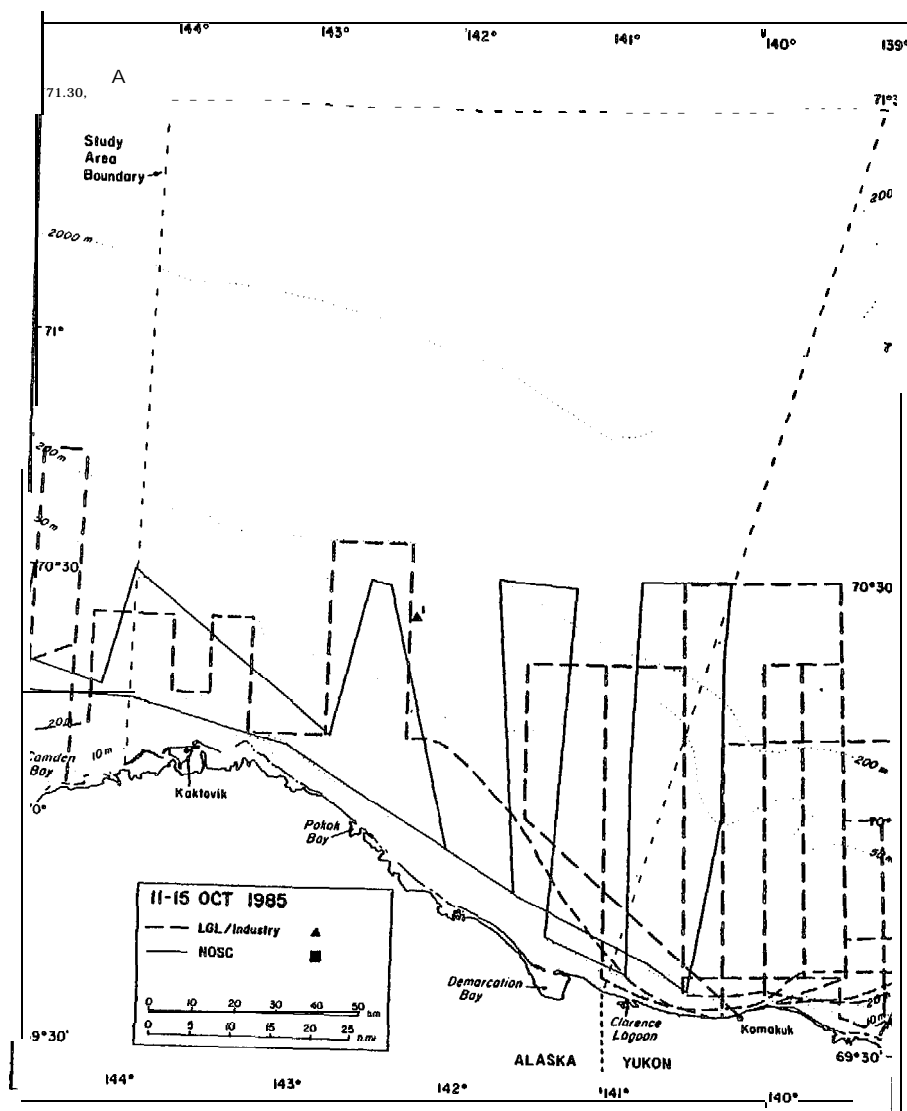


FIGURE 120. Aerial survey routes and bowhead sightings 16-20 October 1985. Sources are Evans and Holdsworth (1986).

during other projects, (A) 11-15 October 1985, and (B) (1986), Ljungblad et al. (1986c) and McLaren et al.

**westward.** Vertical photography demonstrated that some individuals lingered near **Komakuk** for prolonged periods (see p. 319-323). Numerous whales were **still** present farther **east** in Mackenzie Bay (**137°-138°W**) on 14 September when surveys of that area stopped (Davis et al. 1986b).

By 18-21 September, much of the study area (but not the SE corner) contained extensive pack ice, which was blown into the area by strong westerly winds on 16-17 September. **Bowheads** were present in the shelf and shelf break portions of the study area, but none were seen far offshore (Fig. 116A,B). About eight bowheads were seen traveling rapidly westward near the shore at Demarcation Bay on 19 September (Fig. 116A). A few bowheads were seen west of the study area on 19-20 September (Johnson et al. 1986; McLaren et al. 1986.).

By 22-24 September, whales were found in three main areas (Fig. 117): **along** the coast between **Komakuk** and Clarence Lagoon, well offshore north of **Komakuk**, and north of **Kaktovik**. These whales were not moving strongly westward, and were observed or suspected to be feeding. Whales were seen in each of these three areas on two or three different days in the 22-24 September period, and **whales** were seen north of **Kaktovik** on later days as well (Fig. 118). However, vertical photography results provided no evidence that individual whales were lingering off Kaktovik (see p. 326).

On 25 and 27 September, only two bowheads were seen during our systematic survey, most of which was over extensive pack ice. However, there were several sightings north of Kaktovik during reconnaissance surveys on 25-29 September (Fig. 118A, B). Ice cover had become less extensive there than it **was** during the previous week. **Whales** were suspected to be feeding in the water column well offshore from Kaktovik and **Komakuk**. **Whales left** the nearshore waters around **Komakuk** by the 26th. Other workers saw several whales **well** to the west of the study area in late September.

October 1985.--Poor weather conditions from 30 September to 3 October resulted in little survey coverage in early October (Fig. 119A). However, bowheads had apparently left the area off Kaktovik where they had been feeding in late September. A few bowheads were seen farther west during **early** October, including some just west of the official study area (Fig. 119A).

Our field program ended on 3 October, but other projects provided some coverage until 20 October. Bowheads were **still** present in Canadian waters **east** of Herschel Island (**139°W**), in apparently diminishing numbers, **until** at least 18 October (Evans and Holdsworth 1986). Repeated surveys in the **Komakuk** area, both nearshore and offshore, found no bowheads (Fig. 119B, 120A). Only three bowheads were seen in the official study area during October (Fig. 119B, 120A). Coverage of the study area on 16-20 October (Fig. 120B) revealed no bowheads even though there were a few stragglers east of Herschel Island (**139°W**) until at least 18 October. Thus, the surveys suggest that few if any bowheads **fed** in the official study area during October, but that late-migrating bowheads must have travelled west through the study area, largely undetected, during early-mid October.

Summary, 1985.--There were a few bowheads in **the** southeastern part of the official study area in mid-August 1985, but numbers there were low. Contrary to results from some previous years, bowheads were not found in deep parts of

the study area in August 1985. Bowheads were apparently absent from the study area in late August-early September 1985. The western edge of their distribution at this time was just to the east of the official study area. Westward migration through the continental shelf and slope zones began by 11 September (cf. Ljungblad et al. 1986c, p. 39). However, the initial numbers were low. Significant numbers were not seen in the study area until late September, when there were numerous sightings in the mid-shelf area. There were only two sightings in the official study area in October. However, based on sightings farther east, migration apparently continued through the area until at least 18 October.

#### Seasonal Occurrence of Bowheads, Autumn 1986

August 1986.--There were no aerial surveys before 15 August. In mid August, NOSC found bowheads close to shore along the Yukon coast just east of the official study area, and in deep water along the eastern border of that area (Fig. 121A). Bowheads were present in these areas when NOSC first surveyed them, so it is not known when whales first arrived there. NOSC's intensive survey coverage in August extended west to Flaxman Island (146°W). However, the only August sighting west of the eastern edge of the study area was a single whale near the shelf break at 144°35' on 16 August (Fig. 121A). The occurrence of some bowheads in deep water in the eastern part of the Alaskan Beaufort Sea during August is consistent with the typical pattern (cf. Fig. 107A, 112).

September, 1986.--Our surveys began on 3 September, and continued almost daily until 27 September; there were only four days when bad weather prevented effective surveys (Fig. 122A-126A). Additional September coverage was provided by the NOSC/MMS and LGL/industry studies (Fig. 122B-126B). There was little or no ice anywhere within the continental shelf or slope portions of the study area at any time in September 1986, in contrast to the extensive ice after 17 September in 1985.

Whales were present close to shore in early-mid September of 1986. Consequently, part of our survey coverage on most days was along the coast to direct the zooplankton or radio--telemetry crews to whales (Fig. 127). In early September numerous whales fed close to shore at three locations:

1. Off the Kongakut Delta (141°45') within the official study area; first seen on 3 September by the zooplankton crew and on 4 September by Koski and Johnson (in prep.). Probably not present in mid-late August (cf. Fig. 121). We saw at least 30 different whales here on 5 September. Considerable numbers remained here until 7 September. On 8 and 10 September groups of whales were seen several kilometers to the east, off Demarcation Bay (Fig. 127).
2. In the Clarence Lagoon-Demarcation Point area (140°45'-141°00'), where whales had been present as early as NOSC's first flight on 15 August (cf. Fig. 121A).
3. Between Herschel Island and Nuneluk Lagoon (139°15'-139°45'), where whales had been present as early as 20 August (cf. Fig. 121A).

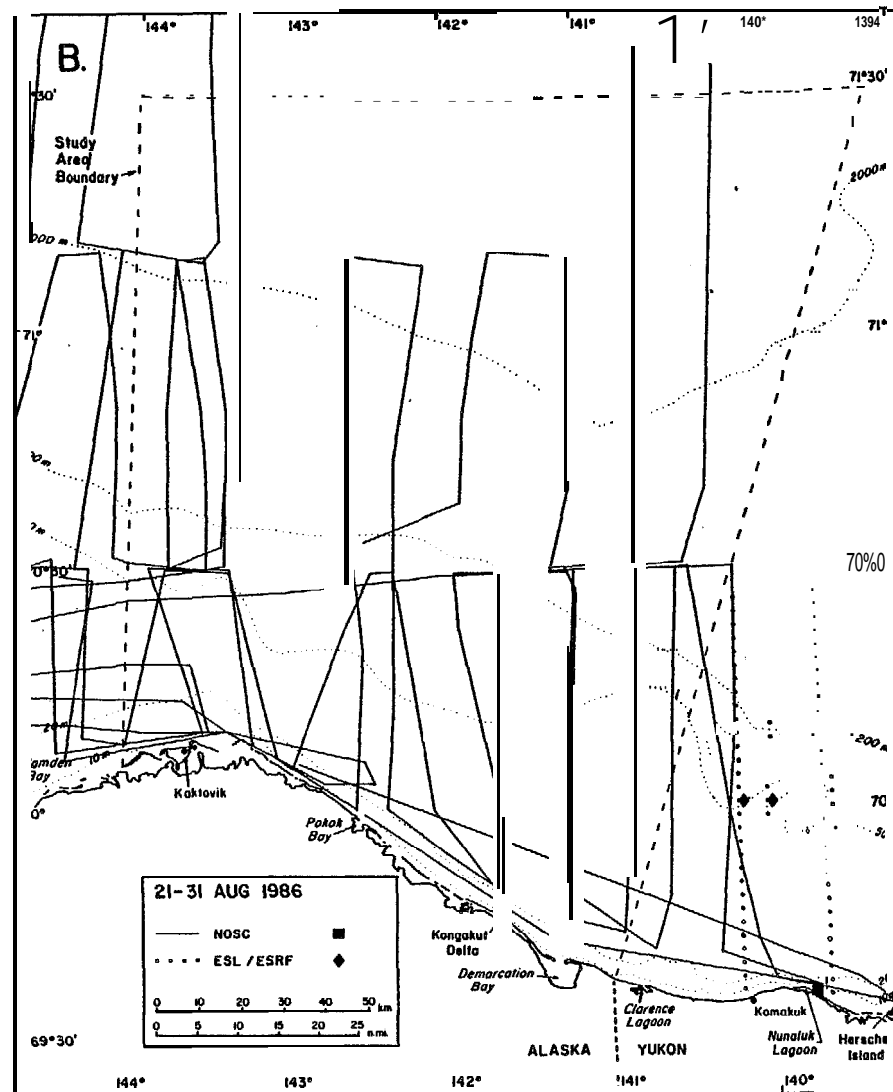
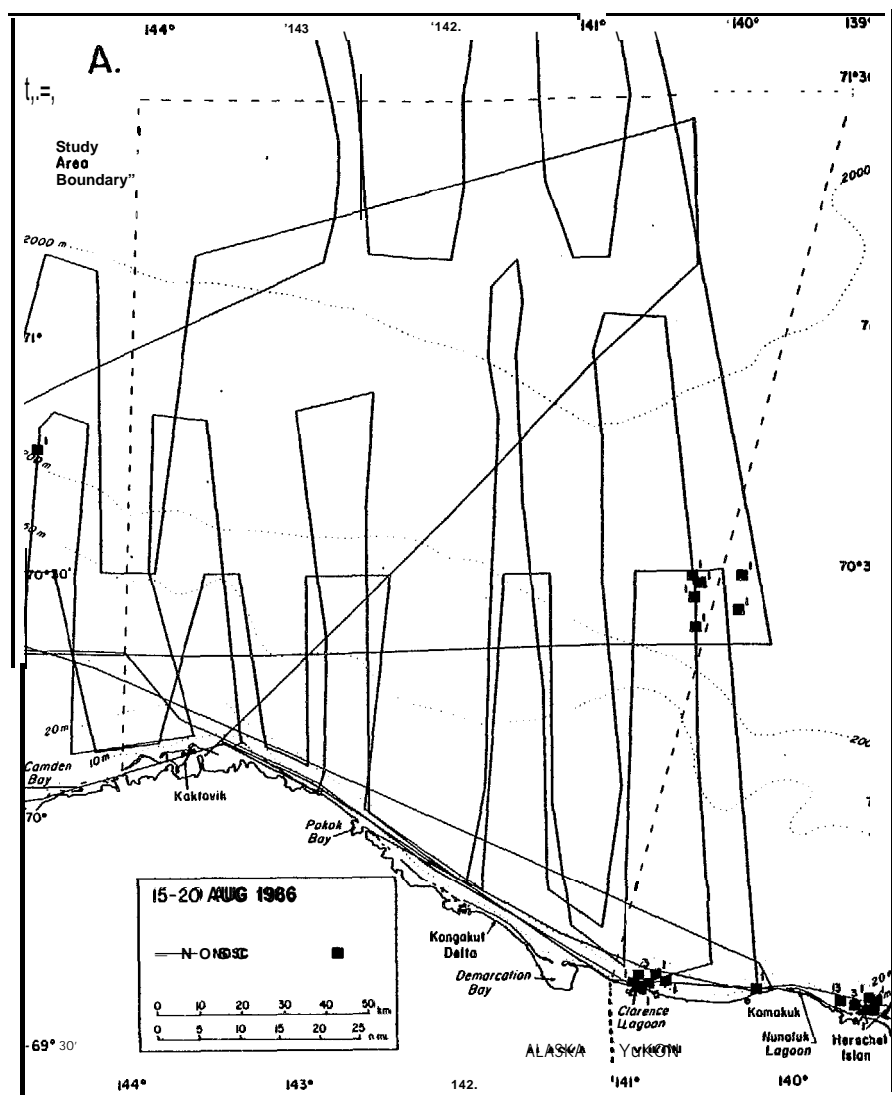


FIGURE 121. Aerial survey routes and bowhead sightings during other projects, (A) 15-20 August 1986, and (B) 21-31 August 1986. Sources are NOSC (unpubl. data) and ESL (unpubl. data).

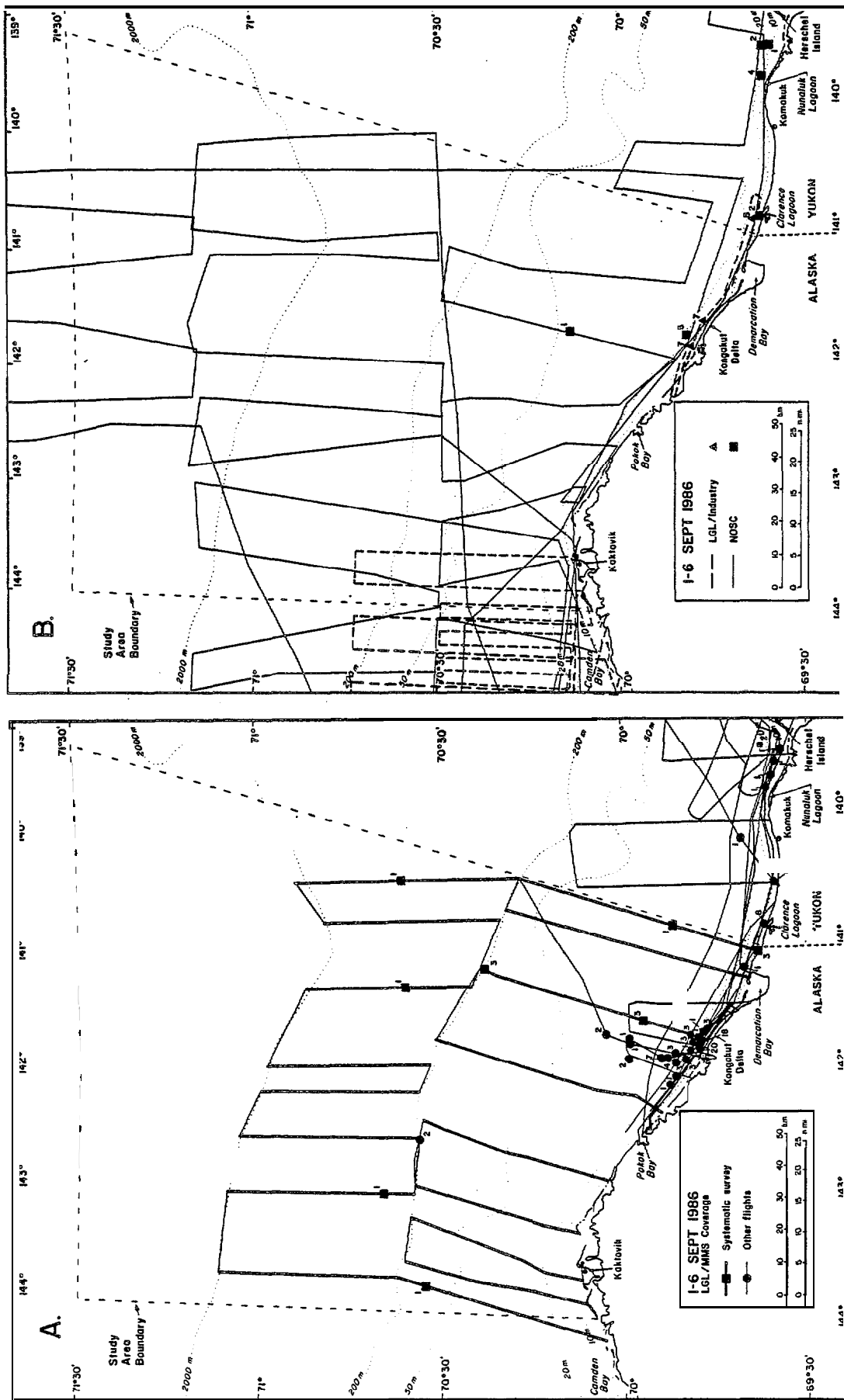


FIGURE 122. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 1-6 September 1986. Sources for (B) are Evans et al. (in prep.), Koski and Johnson (in prep.), and NOSC (unpubl. data).

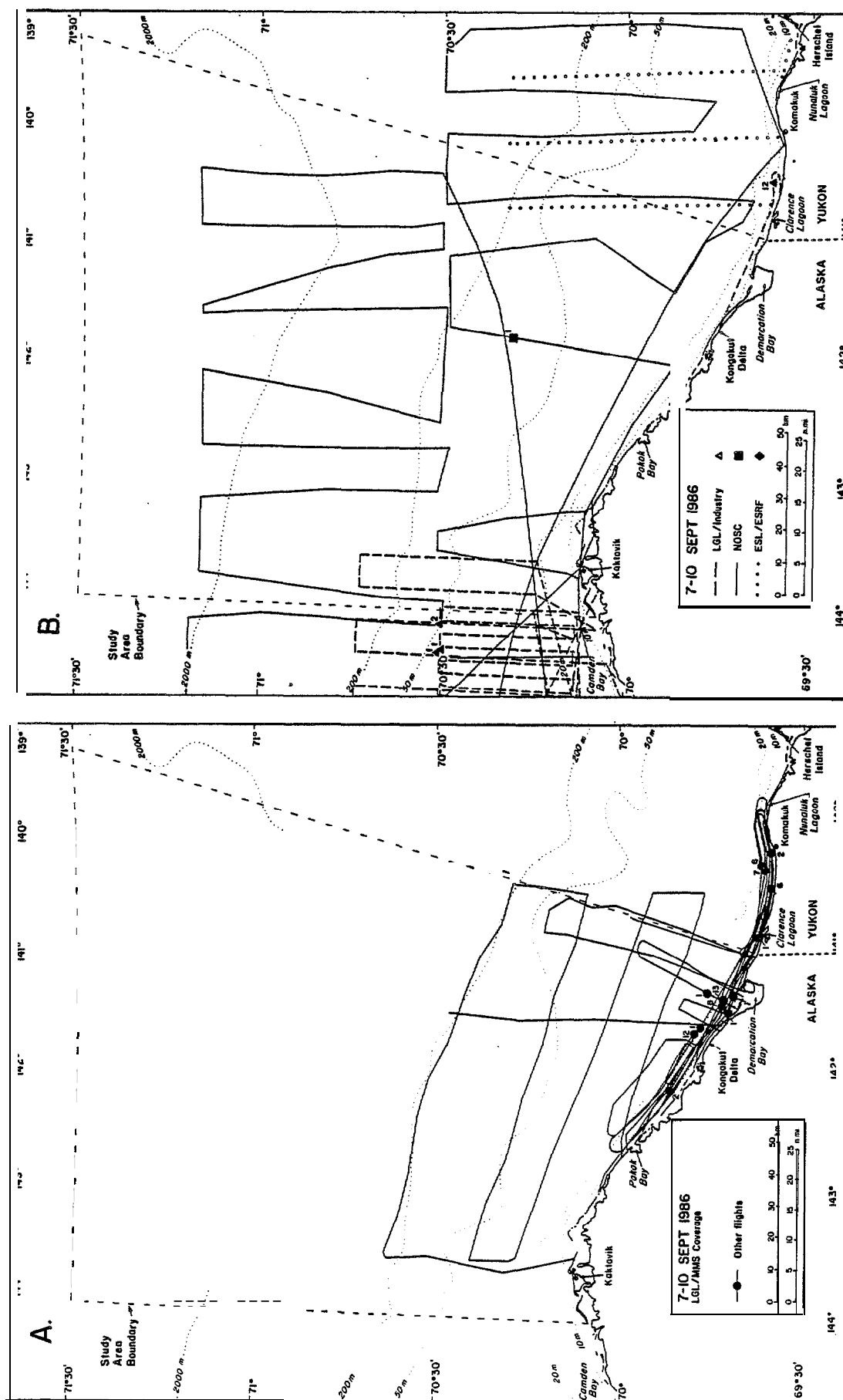


FIGURE 123. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 7-10 September 1986. Sources for (B) as in Fig. 122B, plus Harwood and Norton (1986).

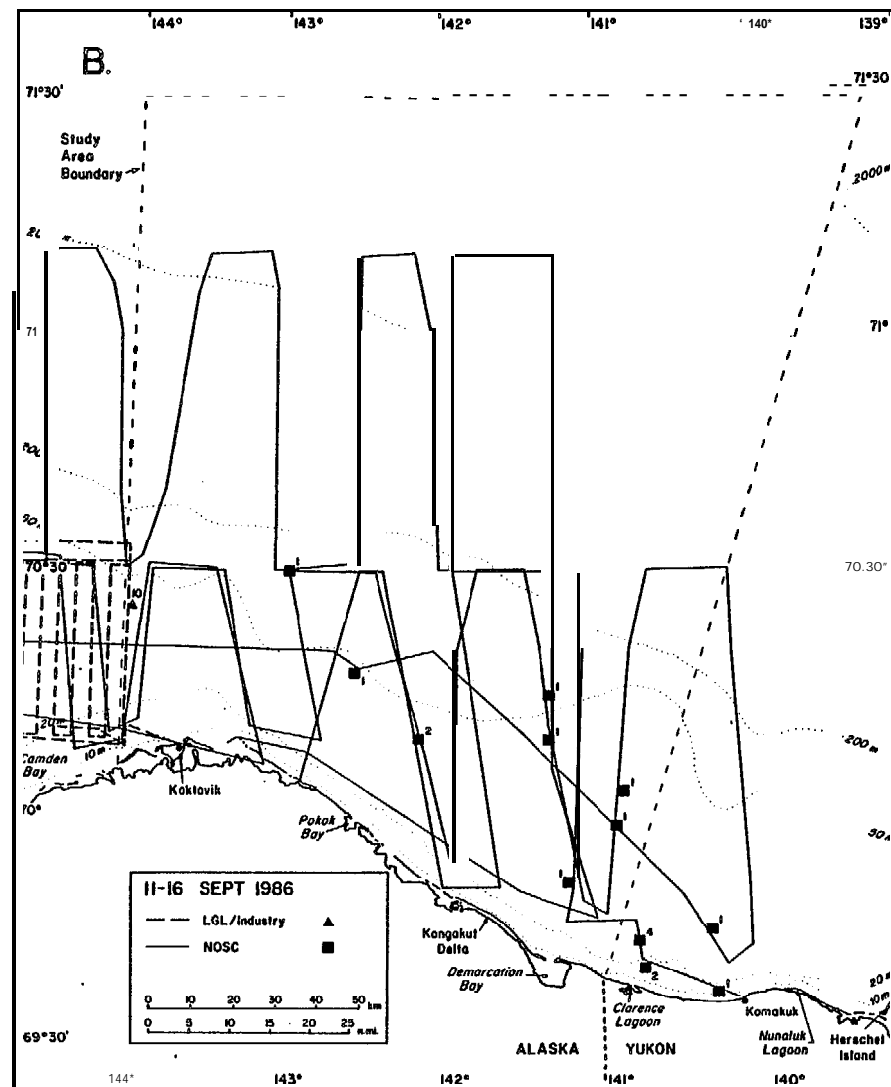
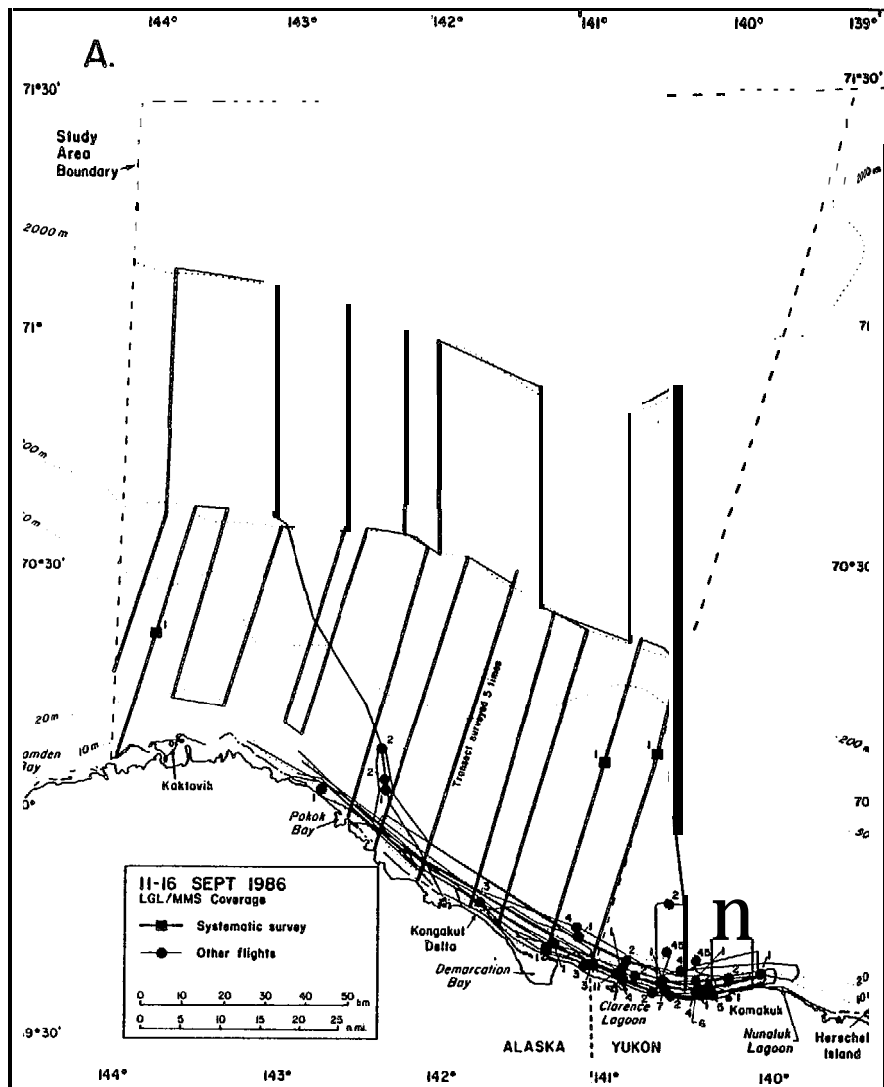


FIGURE 124. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 11-16 September 1986. Sources for (B) as in Fig. 122B.

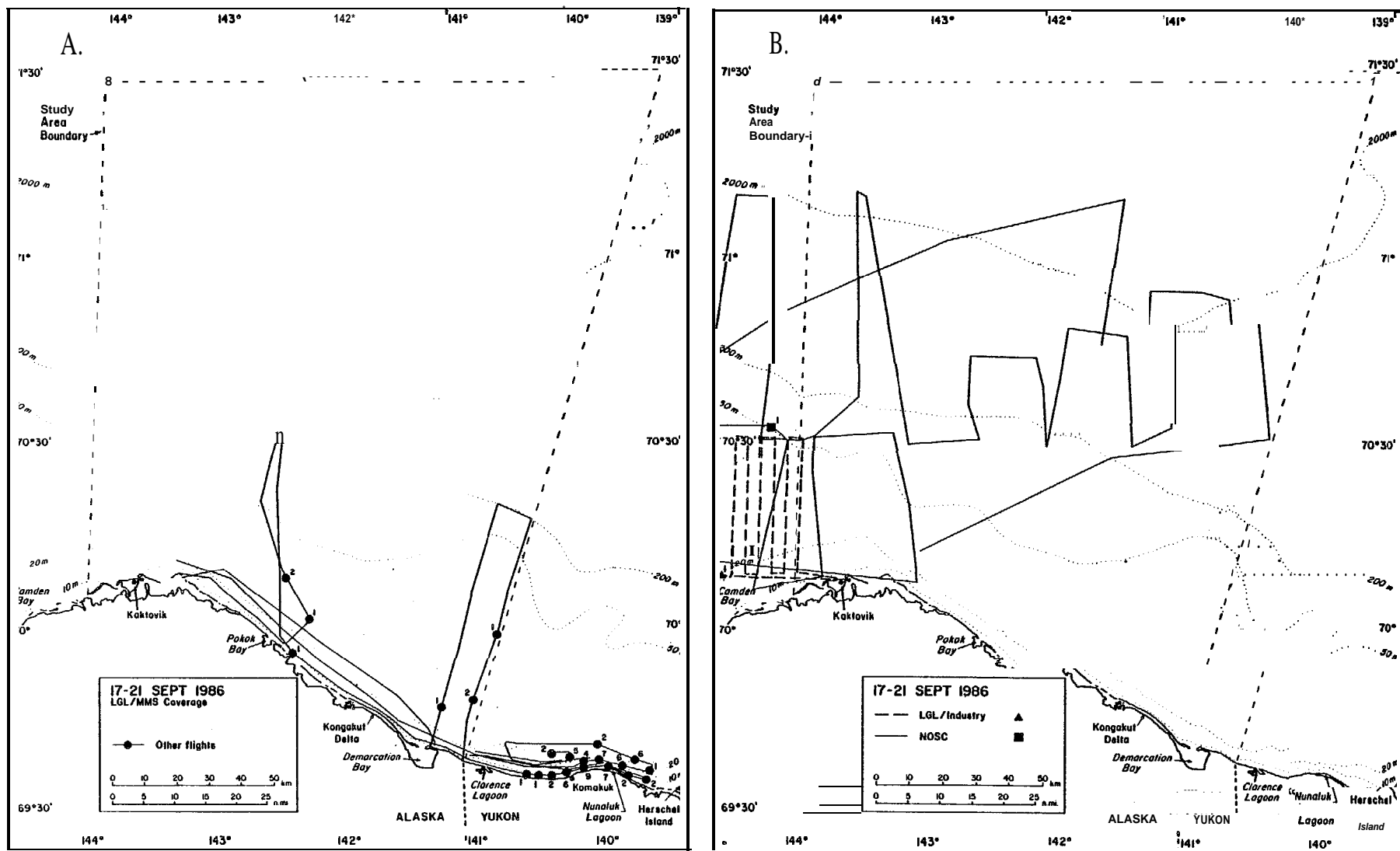


FIGURE 125. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 17-21 September 1986. Sources for (B) as in Fig. 122B.



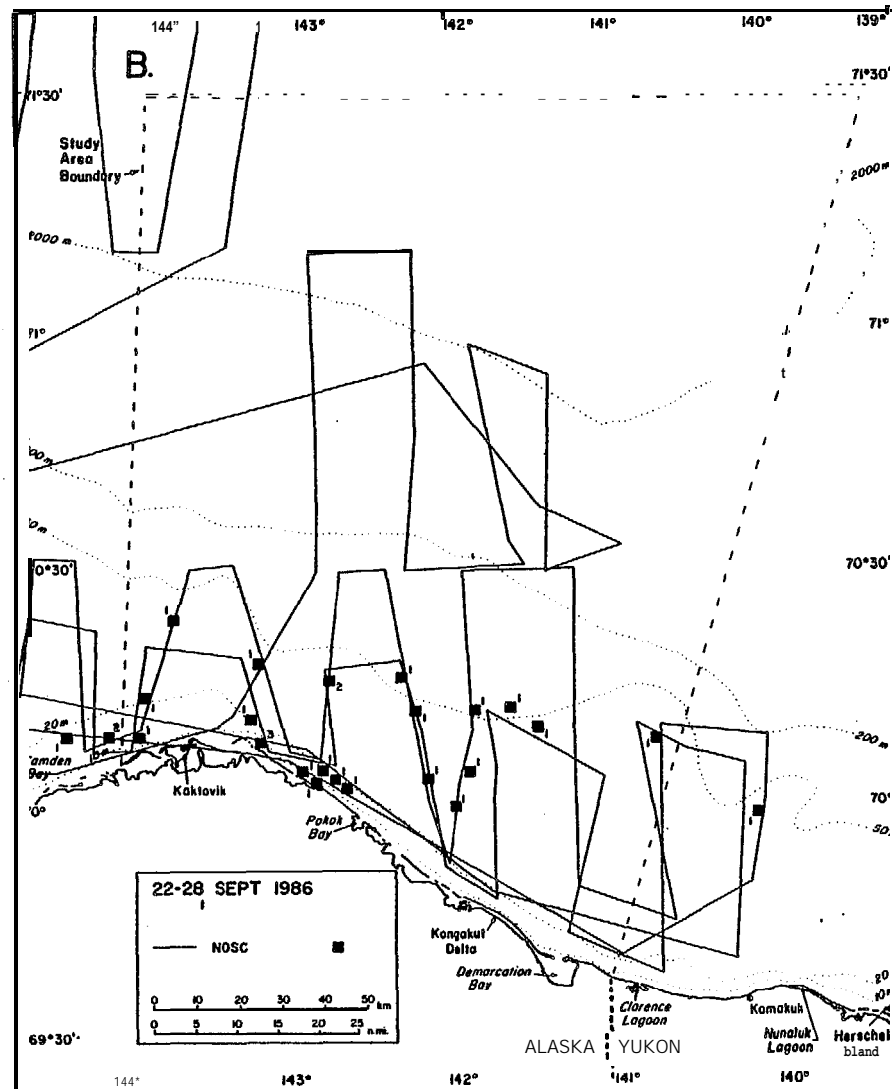
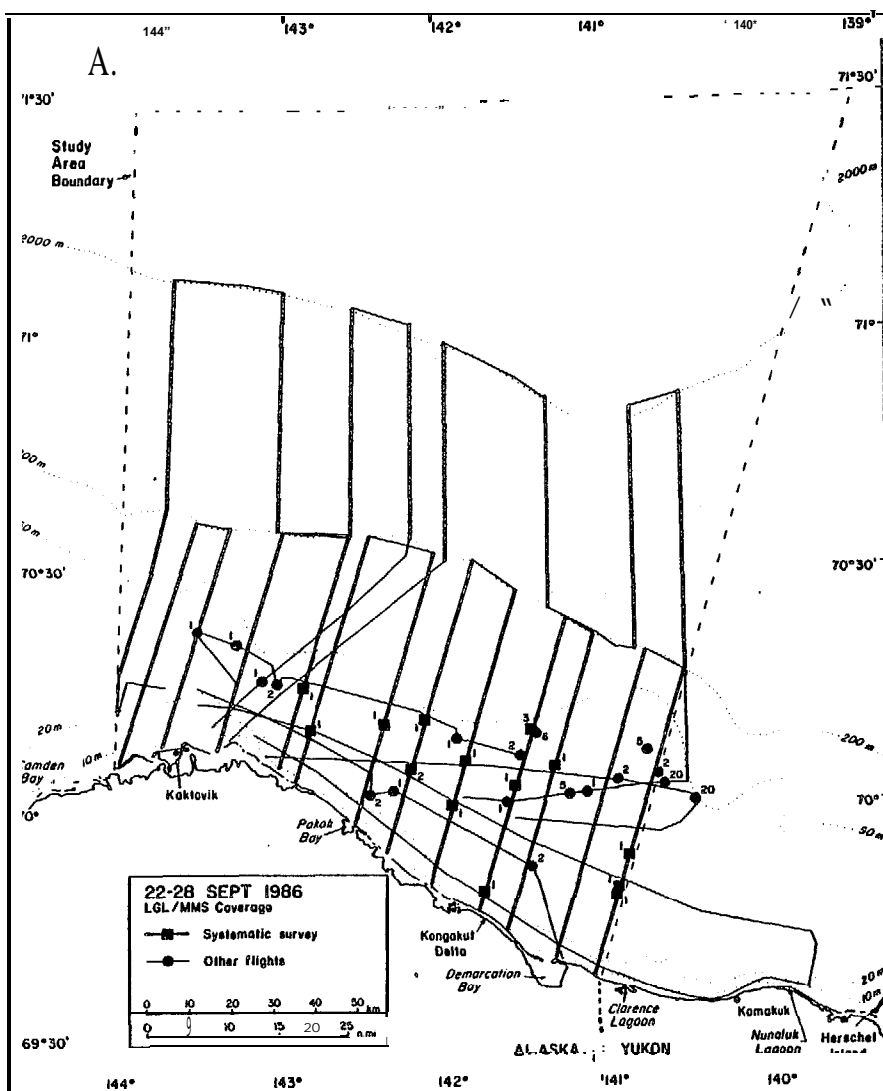
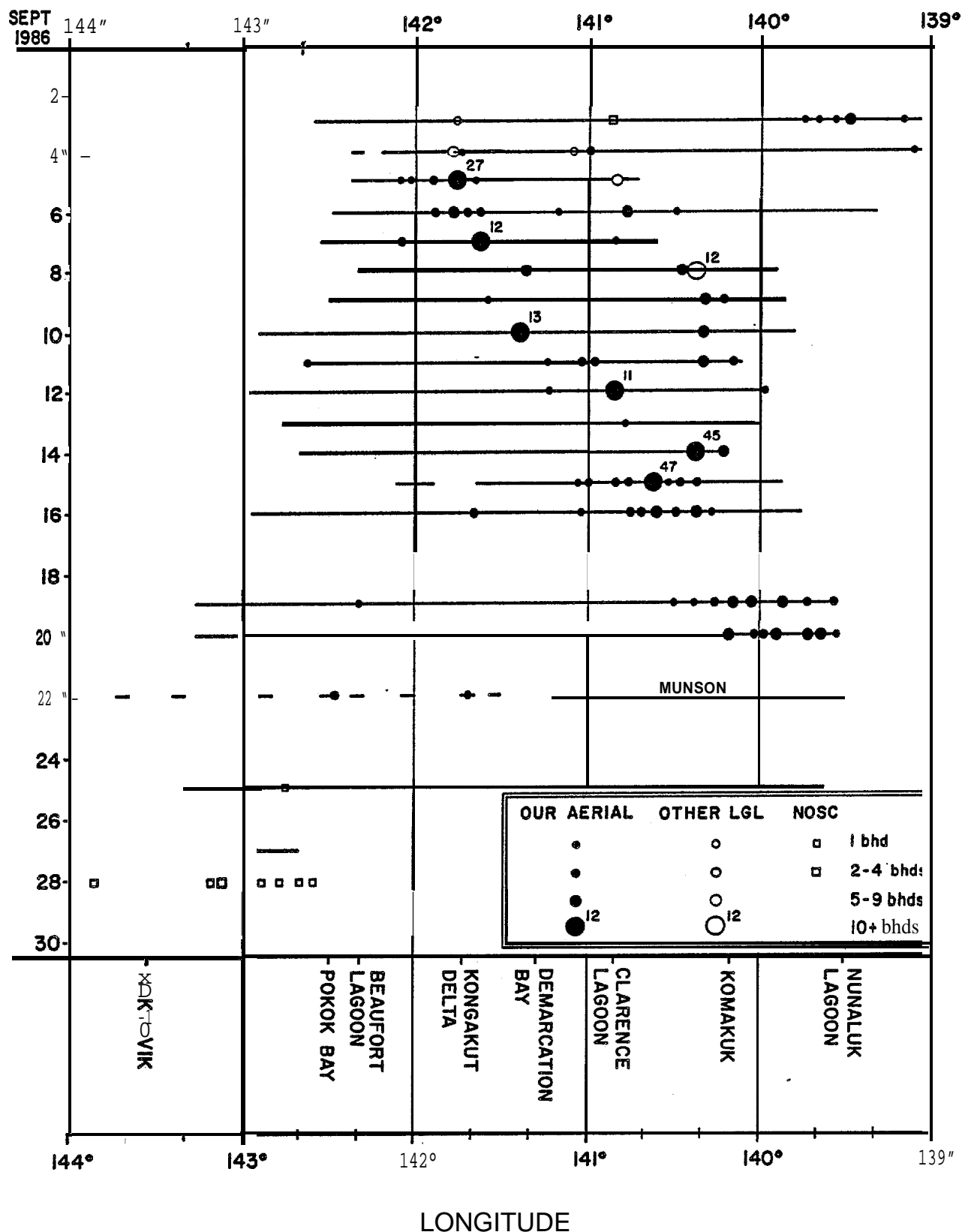


FIGURE 126. Aerial survey routes and bowhead sightings during (A) this project, and (B) other projects, 22-28 September 1986.



**FIGURE 127.** Daily aerial survey coverage and bowhead sightings in nearshore waters, September 1986. Horizontal lines show stretches of coast (<10 km from shore) surveyed from the air during LGL projects. Solid symbols show bowhead sightings during **our aerial** surveys. Open symbols show sightings <10 km from shore by other LGL crews and by NOSC.

In mid September, whales were scarce off the Kongakut Delta (area 1), but many fed along the Yukon coast at varying locations between areas (2) and (3) (Fig. 124, 125, 127). We estimated that there were 50 or more whales along this part of the Yukon coast on each of several dates in mid September. Distances from shore typically ranged from  $\frac{1}{2}$ -10 km. These whales had apparently left by 22 September; none were seen during a boat survey from Nunaluk Lagoon to Demarcation Bay on that date, or during an aerial survey on 25 September (Fig. 126A, 127).

Bowheads were also seen farther offshore, in much lower densities, during early-mid September 1986. During the first systematic survey on 4-5 September we saw nine whales widely distributed across the official study area in waters about 100-1000 m deep (Fig. 122A). Of these, eight were oriented SW, W or NW (Table 28). Most of the whales seen in shallower waters were not oriented west. The first sighting west of the study area (aside from the isolated 16 August whale mentioned earlier) was of about 10 whales off Camden Bay on 9 September (Koski and Johnson in prep.).

Table 28. Headings of bowheads seen during systematic and reconnaissance surveys, September 1986. Behavioral and photo sessions are excluded. Whales heading NE-SSE and SW-NNW (True) were grouped together because they were considered to be travelling roughly parallel to the coast and, respectively, eastward or westward.

Dates in September 1986					
	1-6 <sup>a</sup>	7-10	11-16	17-21	22-28
<b>Depths 50-2000 m</b>					
N - NNE					
NE - SSE	1	-	-	-	-
S - SSW					
SW - NNW	8	-	-	-	-
<b>Depths 20-50 m</b>					
N - NNE	1	-	1	1	1
NE - SSE	1	-	4	1	4
S - SSW	4	-	1	-	-
SW - NNW	3	-	4	3	27

<sup>a</sup> Excludes Flight 6 on 5 Sept, when whale headings were affected by boat disturbance.

By 11 September, there were widespread sightings across the middle shelf area (water depths mainly 30-50 m; Fig. 124A,B), although there was no clear tendency for westward orientation (Table 28; NOSC in prep.). The Kaktovik whalers struck bowheads on 10 and 15 September. Sightings west of the study area became increasingly common in mid September (Koski and Johnson in prep.; NOSC in prep.). However, bowheads were still common in the Canadian Beaufort Sea in mid September, with numerous sightings as much as 375 km east of the study area (Harwood and Norton 1986).

Many bowheads were seen in the middle and inner shelf parts of the study area during late September (Fig. 126). These whales tended to orient westward (Table 28), but there were indications that many were feeding as well "(see later). We found a large concentration of whales near the eastern edge of the study area during our last two days of surveys (26-27 Sept; water depth about 45 m). In late September there were considerable numbers of whales as far east as 130° in the Canadian Beaufort Sea (23 Sept survey of Harwood and Norton 1986) and as far west as Flaxman Island (146°W; Koski and Johnson in prep.; NOSC in prep.). In late September, whales occurred close to shore from Pokok Bay west past Kaktovik (Fig. 126B). The Kaktovik whalers took their third bowhead on 26 September, and acoustic monitoring close to Kaktovik detected many bowhead calls from 27 September to 3 October (Moore et al. 1987). Whales were also seen close to shore at Flaxman Island (Koski and Johnson in prep.). In contrast to the increasing numbers of whales in the middle and inner shelf area in mid and late September, no bowheads were seen far offshore (depths >100 m) after 5 September (Fig. 123-126).

October, 1986---Survey coverage in and near the study area during October was very limited (Fig. 128); our field season had already ended. There were four survey flights into the western portion of the study area on 2-10 October. Bowheads were seen close to shore near Kaktovik on the 2nd (4 seen by Evans et al. in prep.) and 6th (3 seen by NOSC in prep.). The only October survey in the Canadian Beaufort Sea was along part of the Yukon coast on 3 October, when several whales were seen near King Point (138°W) and two at Herschel Island (Harwood and Norton 1986). Many whales were seen in the Flaxman Island area (146°W) and farther west in early October (Evans et al. in prep.; NOSC in prep.). The last bowhead sighting near or east of Prudhoe Bay was a NOSC sighting off Prudhoe Bay on 17 October. However, there is no information with which to determine when the 1986 migration through the study area ended.

Summary, 1986---In mid August 1986, as in August 1985, the western edge of whale distribution was near the eastern edge of the official study area, with only a single isolated sighting farther west. As in most past years, those in the study area in August were offshore in deep water. However, just east of the official study area there were bowheads close to the Yukon shore, as in August of 1984 (Richardson et al. 1985a, 1987) and 1985. In early September 1986, unlike 1985, whales also fed close to shore in the southeastern part of the study area off the Kongakut Delta.

Bowheads began moving west through the official study area, mainly near the shelf break, during the first week of September 1986. This was slightly earlier than in 1985. Thereafter none were seen in deep water, and numbers in the mid shelf area increased. Feeding whales remained along the Yukon coast

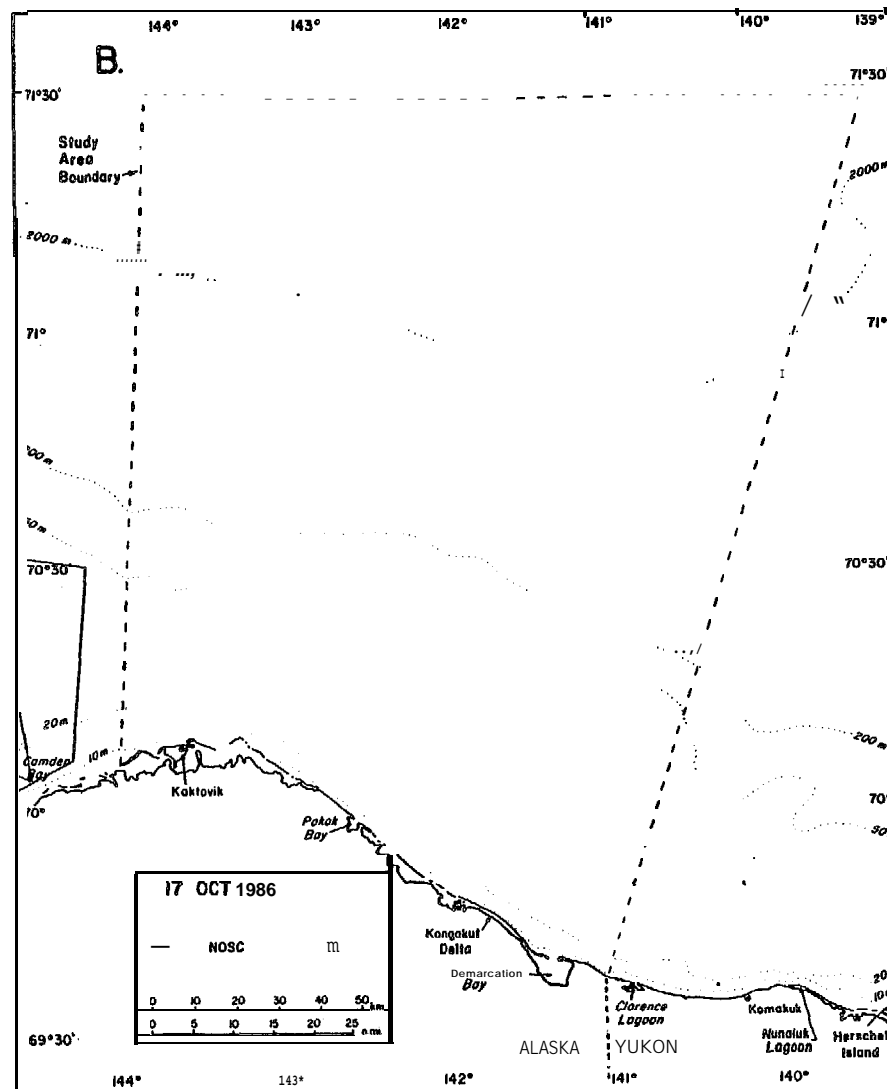
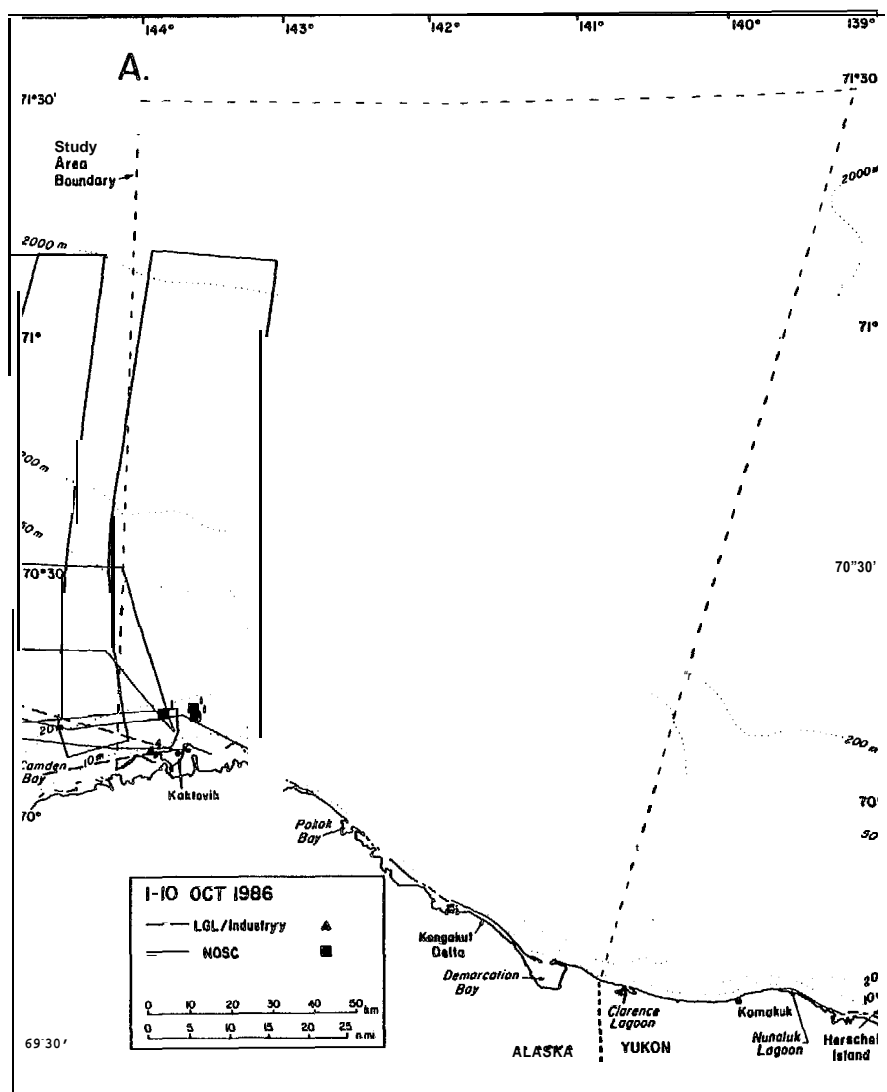


FIGURE 128. Aerial survey routes and bowhead sightings during other projects, (A) 1-10 October 1986, and (B) 11-20 October 1986. Sources as in Fig. 122B.

just east of the official study area until about 20 September, but those that had fed near the Kongakut Delta left earlier. Many whales were in the mid and inner shelf areas in late September, mainly oriented westward but with evidence of some feeding. Late September sightings within the study area were more widespread and more numerous in 1986 than in 1985. There also were more September sightings close to Kaktovik in 1986 than in 1985, and this was reflected in the whaling results: no whales were taken in 1985; three in 1986. The last bowhead sightings in the study area in 1986 were near Kaktovik on 6 October, but survey coverage in October 1986 was meagre.

#### Number of Bowheads in the Study Area

Raw Densities, Autumn 1985. --Only seven bowheads were seen during our four aerial surveys along randomized transects over the continental shelf and our three surveys over the slope. These surveys totalled 4301 km in length and 8602 km<sup>2</sup> in area (Table 29). Three bowheads were on-transect; four were off (i.e. >1.1 or 1.2 km to the side of the aircraft; see Methods, p. 263). The Naval Ocean Systems Center also conducted systematic aerial surveys in the shelf, slope and (occasionally) far" offshore portions of the study area during 1985. NOSC surveyors saw two on-transect bowheads during random north-south surveys within the official study area up to 20 August, but none thereafter.

Based on the randomized survey coverage by LGL and NOSC, raw densities of bowheads in the shelf and slope portions of the study area, expressed as bowheads/100 km<sup>2</sup>, were roughly as follows:

	<u>She 1-f</u>	<u>Slope</u>
1 Aug - 20 Aug 1985	0.07	0
21 Aug - 10 Sept 1985	0	0
11 Sept - 30 Sept 1985	0.06	0.04
1 Oct - 20 Oct 1985	0.05	0

The derivation of these values is given in Richardson et al. (1986b, p. 167-173). These figures are very approximate, given the extremely small number of bowhead sightings during systematic surveys in 1985. However, it is obvious that relatively few bowheads were in the study area at any time during the late summer and autumn period of 1985.

Utilization of the study area by bowheads was much lower in 1985 than in most years. Table 30 summarizes NOSC's 1979-86 randomized survey data for the same depth strata as are used here, although for a somewhat broader range of longitudes (141°-146°W). NOSC found lower densities of bowheads in and near our study area during 1985 than during any other year in the 1982-86 period. (Before 1982, NOSC's randomized coverage of the present study area was limited.)

Raw Densities, Autumn 1986. --We saw 39 bowheads during the three surveys of the 21 randomized transects in September 1986, compared with 7 bowheads during three (continental slope) or four (continental shelf) surveys in 1985. Of the 39 whales, only three were seen along 1284 km of surveys in the continental slope zone; all three of these were seen on-transect during the first survey. The remaining 36 whales were seen along 2190 km of surveys in

Table 29. Results of LGL/MMS systematic aerial surveys of the Alaskan Beaufort Sea, 5-27 September 1985 and 4-25 September 1986.

	1985 Surveys				1986 Surveys		
	1	2	3	4	1	2	3
<b>Continental Shelf Stratum</b>							
Dates	5-6 Sep	12-13 Sep	18 Sep	25-27 Sep	4-5 Sep	11-15 Sep	22-25 Sep
Transects surveyed	1-8, BL1, BL2 <sup>a</sup>	1-13, BL1, BL2 <sup>a</sup>	1-13	1-13	1,2,4,6,8, 10-13	1-13	1-13
km flown	675	879	811	832	563/533 <sup>b</sup>	795/745 <sup>b</sup>	832/782 <sup>b</sup>
No. bowheads seen							
On-transect	0	1	1	1	8/5	7/3	5/5
Off-transect	0	0	2	0	4/3	0/0	12/12
Bowheads/100 km <sup>2</sup> (On-transect data)	0.0	0.057	0.062	0.060	0.71/0.47	0.44/0.20	0.30/0.32
Bowheads/100 km (On- & Off-transect)	0.0	0.11	0.37	0.12	2.13/1.50	0.88/0.40	2.04/2.17
<b>Continental Slope Stratum</b>							
Dates	-	12 Sep	19-21 Sep	27 Sep	5 Sep	14-15 Sep	25-26 Sep
Transects surveyed	-	14-21	14-19	14-21	4-21	14-21	14-21
km flown	0	428	318	358	428	428	428
No. bowheads seen							
On-transect	-	0	0	0	3	0	0
Off-transect	-	1	0	1	0	0	0
Bowheads/100 km <sup>2</sup> (On-transect data)	-	0.0	0.0	0.0	0.35	0.0	0.0
Bowheads/100 km (On- & Off-transect)	-	0.23	0.0	0.28	0.70	0.0	0.0

<sup>a</sup> BL1 = Boat Line 1, BL2 = Boat Line 2 (see Fig. 114A, 115A). Aerial surveys of these lines during the survey 1 and 2 periods were considered to be part of the systematic survey coverage.

<sup>b</sup> For 1986 surveys in the shelf stratum, results are given as All data/All data excluding 10 x 50 km nearshore strip off Kongakut Delta and Demarcation Bay (see text).

Table 30. Survey results from the Naval Ocean Systems Center's randomized north-south (approx. ) surveys within the Eastern Alaskan Beaufort Sea ( 141°-146°W longitude) during August-October in 1979-86. 1979-84 data supersede those in Richardson et al. ( 1986s, p. 174), which were based on incorrect values in Ljungblad et al. (1984a, 1985a, 1986b)<sup>a,b</sup>.

Year	Depth <sup>a</sup> (m)	August			September			October		
		Coverage (km <sup>2</sup> )	No. of Bowheads	#/100 km <sup>2</sup>	Coverage (km <sup>2</sup> )	No. of Bowheads	#/100 km <sup>2</sup>	Coverage (km <sup>2</sup> )	No. of Bowheads	#/100 km <sup>2</sup>
1979 <sup>a</sup>	>2000	0	0	—	0	0	(0) <sup>b</sup>	4	0	(0) <sup>b</sup>
	200-2000	421	3	(0.71) <sup>b</sup>	198	0	(0) <sup>b</sup>	84	0	(0)
	<200	3827	1	0.03	3817	0	0	1803	2	0.11
1980 <sup>a</sup>	>2000	0	0		0	0		0	0	—
	200-2000	0	0		0	0		0	0	
	<200	0	0		0	0		0	0	
1981 <sup>a</sup>	>2000	0	0		0	0		28	0	( 0 )
	200-2000	0	0		0	0		961	0	(0)
	<200	0	0		74	0	(0)	1748	1	0.06
1982 <sup>a</sup>	>2000	3626	4	0.11	2178	4	0.18	2	0	(0)
	200-2000	5095	38	0.75	2047	0	0	92	0	(0)
	<200	7107	3	0.04	4090	0	0	1590	0	0
1983 <sup>a</sup>	>2000	3905	0	0	2243	0	0	58	0	(0)
	200-2000	3265	0	0	2917	4	0.14	976	0	(0)
	<200	2469	0	0	2829	2	0*07	1391	0	0
1984 <sup>a</sup>	>2000	3049	0	0	2284	0	0	0	0	
	200-2000	3701	0	0	1598	1	0.06	437	0	(0)
	<200	4784	3	0.06	3025	6	0.20	1079	0	0
1985	>2000	1221	0	0	2168	0	0	231	0	(0)
	200-2000	3339	0	0	2399	0	0	1185	0	0
	<200	5431	1	0.02	3387	0	0	2803	0	0
1986	>2000	2237	0	0	2697	0	0	61	0	(0)
	200-2000	2729	1	0.04	4258	0	0	482	0	(0)
	<200	5331	0	0	6495	15	0.23	1023	0	0
<hr/>										
TOTAL	>2000	14037	4	0.03	11569	4	0.03	383	0	(0)
1979-86 <sup>a</sup>	200-2000	18549	42	0*23	13417	5	0.04	4217	0	0
	<200	28949	8	0.03	23717	23	0.10	11436	3	0.03

<sup>a</sup> 1979-84 values are based on pre-publication corrected survey coverage and sighting totals supplied by J. Clarke (pers. comm., Aug 1987). 1985 values are based on Ljungblad et al. (1986c). 1986 values are based on pre-publication data supplied by J. Clarke (pers. comm., Feb 1987).

<sup>b</sup> parentheses indicate that density is based on <1000 km<sup>2</sup> of survey coverage.



the continental shelf zone (20 on-transect; average density 0.46 bowheads/100 km<sup>2</sup>). Based on on-transect sightings, bowhead abundance in the shelf zone seemed to be declining from early to mid to late September (densities 0.71, 0.44 and 0.30 bowheads/100 km<sup>2</sup>, respectively). However, this trend was not evident when off- as well as on-transect whales are considered (Table 29).

The high average density in the shelf zone in early-mid September was largely attributable to the concentration of bowheads feeding near shore off the Kongakut Delta and Demarcation Bay. Three of 8 whales seen on-transect in early September were in that area, as were 4 of 7 seen in mid-September. Hence, we recalculated the densities for the continental shelf zone, excluding surveys and sightings in a 10-km by 50-km strip along the shore from Beaufort Lagoon to Demarcation Point. Excluding this feeding area, the raw densities in the shelf zone during early, mid and late September were 0.47, 0.20 and 0.32 bowheads/100 km<sup>2</sup> (Table 29).

The Naval Ocean Systems Center also conducted randomized surveys within the continental shelf and slope portions of our study area in 1986. Their 1986 coverage began earlier in the season than ours, and ended later (15 August - 10 October). NOSC also conducted limited surveys in the far offshore part of the official area (depths >2000 m) where we did not work. Based on preliminary maps of flight routes and sightings provided to us by NOSC, we estimated the amount of randomized survey coverage obtained by NOSC within the shelf, slope and far offshore parts of the official study area in 1986. We excluded NOSC's 'connect' and 'search' coverage and sightings (see Ljungblad et al. 1986c for definitions). From these NOSC data, we calculated raw densities of bowheads in three depth strata (Table 31).

NOSC detected no bowheads in the far offshore part of our study area (depths >2000 m) during 1986, and saw bowheads in the continental slope zone (depths 200-2000 m) only in the mid-August period (Table 31; Fig. 121-128). However, our surveys showed that bowheads were still present in the slope zone in early September (Table 29; Fig. 122A).

NOSC found no bowheads in the continental shelf zone (depths 0-200 m) in mid or late August 1986, before our field season began. NOSC's data from that zone in early, mid and late September 1986 give raw densities of 0.14, 0.21 and 0.33 bowheads/100 km<sup>2</sup>. NOSC's randomized north-south transects provided essentially no coverage of the main feeding area off the Kongakut Delta in early-mid September (Fig. 122B-125B). Thus, their density figures should not be considered representative for the continental slope zone as a whole. Instead, NOSC's data are most directly comparable to our figures for the shelf zone exclusive of the nearshore strip off the Kongakut Delta and Demarcation Bay (all values in bowheads/100 km<sup>2</sup>):

	<u>1-10 Sept</u>	<u>11-21 Sept</u>	<u>22-28 Sept</u>
NOSC	0.14	0.21	0.33
LGL	0.47	0.20	0.32

The mid and late September results from the two studies are remarkably similar. However, our densities for the shelf zone in early September considerably exceeded those obtained by NOSC. As noted earlier, we also saw

Table 31. NOSC survey coverage and bowhead densities within our official study area, 15 August-10 October 1986. Only transects oriented roughly north-south are considered. Based on unpublished data (NOSC in prep. ) from both NOSC survey aircraft . On-transect whales were considered to be those 200-1200 m laterally from the flight lines. However, there were no sightings 0-200 or 1000-1200 m to the side along these lines so this assumption was not critical .

Dates	Continental Shelf (0-200 m deep)				Continental Slope (200-2000 m deep)				Far Offshore (>2000 m deep)		
	Coverage (km)	No. Hds On/Off	Density (/100 km <sup>2</sup> )		Coverage (km)	No. Hds On/Off	Density (/100 km <sup>2</sup> )		Coverage (km)	No. Hds On/Off	Density (/100 km <sup>2</sup> )
15-20 Aug	846	0/0	o		398	3/0	(0.38) <sup>a</sup>		387	0/0	(0) <sup>a</sup>
21-31 Aug	845	0/0	o	"	557	0/0	o		321	0/0	(o)
1-10 Sept	703	2/0	0.14		854	0/0	" o		609	0/0	o
11-21 Sept	959	4/3	0.21		665	0/0	o		159	0/0	(o)
22-28 Sept	601	4/9	0.33		215	0/0	(0)		104	0/0	(0)
1-10 Oct	106	0/0	(0) <sup>a</sup>		87	0/0	(o)		15	0/0	(0)

<sup>a</sup> Parentheses indicate that density is based on <1000 km<sup>2</sup> (i.e. <500 linear km) of coverage.

whales in the continental slope portion of the study area in early September whereas NOSC did not.

There are no data with which to estimate the raw density of bowheads in the study area in October 1986. Our surveys ended on 27 September. NOSC's randomized coverage of the study area in October was very limited (Table 31). NOSC detected no bowheads in the area during their randomized October coverage. However, they and Evans *et al.* (in prep,) both found whales in the shelf zone during reconnaissance flights. Also, NOSC's acoustic monitoring near Kaktovik suggested that bowheads were common there until 3 October and present until at least 7 October (Moore *et al.* 1987). Thus, the density in the shelf zone in early October was clearly non-zero, but there are no quantitative data from which a density could be calculated.

For 'purposes of calculating the number of 'whale-days' within the study area, it is necessary to have an estimate of density for all portions of the period when whales might be present. The randomized survey coverage by ourselves and NOSC provides usable values for mid August to late September 1986, but not for early August or for October. Table 32 shows the assumed raw densities in the various parts of the study area in 1986. We emphasize that the early-mid September values for the continental shelf zone exclude the area of whale concentration off the Kongakut Delta and Demarcation Point. The number of whales there can be estimated most accurately from the frequent coastal reconnaissance flights and the behavioral observation and photogrammetry sessions in that area (Fig. 127).

Table 32. Assumed raw densities of bowheads (bowheads/100 km<sup>2</sup>) in the study area, 1986.

	Shelf	Slope	Far Offshore
11-20 Aug	0 <sup>a</sup>	(0.38) <sup>a,c</sup>	(0) <sup>a,c</sup>
21-31 Aug	0 <sup>a</sup>	0 <sup>a</sup>	(0) <sup>a</sup>
1-10 Sept	0.28 <sup>b</sup>	0.12 <sup>b</sup>	0 <sup>a</sup>
11-21 Sept	0.21 <sup>b</sup>	0 <sup>b</sup>	(0) <sup>a</sup>
22-30 Sept	0.33 <sup>b</sup>	0 <sup>b</sup>	(0) <sup>a</sup>
1-10 Oct	(0.10) <sup>d</sup>	(0) <sup>d</sup>	(0) <sup>d</sup>

<sup>a</sup> NOSC data (Table 31).

<sup>b</sup> Pooled results from this study (Table 29, excluding feeding area off Kongakut Delta from 'Slope' stratum) and NOSC (Table 31).

<sup>c</sup> Densities in parentheses based on <1000 km<sup>2</sup> of survey coverage.

<sup>d</sup> No quantitative data; estimated value.

Correction Factor for Submerged Whales. --Bowhead whales are below the surface and invisible to aerial surveyors the majority of the time. If **all** surfacings are of duration  $s$ , **all** dives are of duration  $u$ , and the duration of potential detectability is  $t$ , the probability that a **whale** will be at the surface while it can be seen is

$$\frac{s}{s+u} + \frac{t}{s+u} = \frac{s+t}{s+u}$$

(Eberhardt 1978). Here,  $s/(s+u)$  is the probability that the whale will be at the surface when its location first comes into visual range, and  $t/(s+u)$  is the probability that the whale **will** surface **while** its location is in **visual range**. Davis et al. (1982) estimated that  $t$  was 18 s during their surveys from a Twin Otter aircraft, and we have also used this value. The uncorrected estimate of the number of animals present can be divided by **this** correction factor, viz.  $(s+t)/(s+u)$ , to allow for animals that are undetectable because they **are below** the water as the survey aircraft passes.

The above formula assumes that  $t \leq u$  and that  $s$  and  $u$  are constants. In fact, some dives are very short ( $u < t$ ), and  $s$  and  $u$  are both highly variable (Würsig et al. 1984, 1985b; Ljungblad et al. 1984b, 1985b; this study, p. 342-343). Eberhardt (1978) and Eberhardt et al. (1979) expressed concern about the legitimacy of the  $(s+t)/(s+u)$  formula under these conditions. Davis et al. (1982) developed a modification of the formula that **allows** for short dives, and variable durations of surfacings and dives.

Behavioral observations during **the** 1985 phase of this study provided information about the durations" of 16 surfacing/dive sequences, excluding those of calves and those near boats (Table 33A). We considered **all** known dive durations for which the duration of either the preceding or the following surfacing was **known**. If durations of both adjacent surfacings were known, the average was used. **All** of the timed dives were >1 min in **duration**. Hence, the modified method of Davis et al. (1982) was not needed for the September 1985 data, and any uncertainty in the estimate of  $t = 18$  s was of very **little** consequence. The mean surface and dive durations for **the** 16 timed sequences were 99 and 856 s (1.65 and 14.27 rein), respectively. Hence, bowheads were **at** the surface only 10% of the time, and **only** 12% of the on-transect **bowheads** would be expected to be detectable (Table 33A).

In September of 1986, we measured durations of 30 surfacing/dive sequences (Table 33B). **Also**, in September and early October 1986, another LGL crew using the same methods measured 75 sequences (Koski and Johnson in prep.; Table 33C). Some of the latter data were obtained within the study area; the remainder were obtained <100 km west of the west edge of the study area.

Based on the combined 1986 data from both studies (Table 33D), bowhead whales were at the surface **11%** of the time, and about 14% of the whales **would** be detectable during surveys. The method of Davis et al. (1982, p. 53 **ff**) was used to obtain this 14% estimate, although the uncorrected **value** was almost identical in this case (Table 33D). **Whales** that were close to shore in the Kongakut Delta to Herschel Island area were at the surface more of the time than were those farther offshore (15.4% vs. 10.5%). Thus a higher proportion

**Table 33. Calculation of the probability that an average on-transect bowhead whale will be at the surface while within an observer's field of view. Presumably undisturbed whales plus those exposed to noise pulses from distant seismic vessels are included; whales exposed to nearby boats are excluded. All calf data are excluded.**

	Sum of dive durations	Sum of surface times	# dives and surfacings	Mean Surface time (s)	Mean dive time (u)	$\frac{s + 18}{s + u}$
<b>A. September 1985 (this study)</b>						
Dives <18 s			0			
Dives >18 s	13,701	1581	16	98.8	856.3	0.122
<b>B. September 1986 (this study)</b>						
Dives <18 s	207	170.5	15	11.4	13.8	—
Dives >18 s	6031	926	15	61.7	402.1	0.172
All dives	6238	1096.5	30	36.6	207.9	0.223
					Corrected <sup>a</sup>	0.215
<b>C. Sept-Oct 1986 (LGL/Industry study)</b>						
Dives <18 s			0			
Dives >18 s	62,513	7697.5	75	102.6	833.5	0.129
<b>D. Sept-Oct 1986 (both Stalks)</b>						
Dives <18 s	207	170.5	15	11.4	13.8	—
Dives >18 s	68,544	8623.5	90	95.8	761.6	0.133
All dives	68,751	8794	105	83.8	654.8	0.138
					Corrected <sup>a</sup>	0.137
<b>E. Sept 1986, &lt;10 km from shore (both studies)</b>						
Males <18 s	196	159.5	14	11.4	14.0	—
Dives >18 s	10,625	1812	28	64.7	379.5	0.186
All dives	10,821	1971.5	42	46.9	257.6	0.213
					Corrected <sup>a</sup>	0.209
<b>F. Sept-Oct 1986, &gt;10 km from shore (both studies)</b>						
Dives <18 s	11	11	1	11	11	—
Dives >18 s	57,919	6811.5	62	109.9	934.2	0.122
All dives	57,930	6822.5	63	108.3	919.5	0.123
					Corrected <sup>a</sup>	0.122

<sup>a</sup> See Davis et al. (1982) for method of calculating corrected  $(s + t)/(s + u)$ . For 'B. September 1986 (this study)', the corrected value is

$$\frac{[(207 + 170.5) \times 1.0] + [(6031 + 926) \times 0.172]}{(6238 + 1096.5)} = 0.215$$

of the **whales** along the shore **than of** those farther offshore would **be** detected during aerial surveys (20.9% vs. **12.2%**; Table 33E vs. **33F**).

The few previous estimates obtained with comparable methods are as follows:

	Proportion of time at <u>surface</u>	Detection <u>probabil.</u>
Summer 1981, E Beaufort (Davis et al. 1982)	15-22.5%	0.261
Shammer 1982, E Beaufort (data of Würsig et al. 1985b) <sup>a</sup>	<b>17.3%</b>	<b>0.205</b>
Autumn 1978-79, Baffin Isl. (data of Koski and Davis 1979, 1980) <sup>a</sup>	15.5%	<b>0.184</b>

<sup>a</sup> Data from these studies were **re-analyzed** by Richardson et al. (1986b, p. 176).

Previous studies have given higher proportions of time at the surface and higher detection probabilities than we found in September 1985 or for whales offshore in autumn 1986. Nonetheless, we believe that the 1985-86 results are realistic. Our general impression was that most bowheads were diving for long periods and surfacing for short periods, at **least** in offshore areas. Furthermore, data from earlier years **also** suggest that the proportion of time at the surface is **lower** in Alaskan waters in early **autumn** than in the Canadian **Beaufort** Sea in summer (**13.1%** vs. 21.2%; **Table 34**). Thus, we consider the 1985-86 data on proportion of time at surface and detection probability **to be** appropriate figures for use in estimating the number of bowheads missed by aerial surveyors.

Correction Factor for Unseen Bowheads at the Surface.--Besides missing submerged **bowheads**, aerial surveyors **fail** to detect some of **the** bowheads that are at the surface as the aircraft passes. **In an** attempt to estimate the proportion missed, **two** surveyors observed independently from the right side of the aircraft during most of the systematic surveys conducted during this **study**. There were 17 sightings of one or more **bowheads** by right-side observers during these surveys. Of these, six were by both observers ( $B = 6$ ), five by only the front observer ( $S_1 = 5$ ), and six by only the rear observer ( $S_2 = 6$ ). Considering only on-transect whales, the figures were  $B = 4$ ;  $S_1 = 4$  and  $S_2 = 3$ . Based on the method of Magnusson et al. (1978), the estimated number of singles or groups present **along** these transects was

$$N = \frac{(S_1 + B + 1)(S_2 + B + 1)}{(B + 1)} - 1 = 21.3$$

considering **on-** and off-transect whales, or 13.4 considering on-transect whales **only**. The **actual** numbers of singles or groups sighted by one or both observers were 17 of the estimated  $N = 21.3$  on- **plus** off-transect (80%), and 11 of the estimated  $N = 13.4$  on-transect (82%).

**Table 34.** Durations of surfacings and dives by bowhead whales in the Canadian and Alaskan Beaufort Sea, 1980-84. All data were obtained in the absence of potential disturbance, with the possible exception of aircraft disturbance in Alaska. Calves are excluded.

	Canada <sup>a</sup>			Alaska <sup>b</sup>		
	Mean	s.d.	n	Mean	s.d.	n
<b>Duration of Surfacing (min)</b>						
1980	1.25	0.723	94	-	-	-
1981	1.06	0.764	204	1.82	0.94	42
1982	2.05	1.320	70	1.41	0.57	36
1983	1.05	1.484	248	1.33	1.10	168
1984	1.10	0.559	99	1.19	0.87	155
All	1.19	1.137	715	1.34	0.98	401
<b>Duration of Dive (min)</b>						
1980	2.25	3.549	25	-	-	-
1981	3.80	4.986	80	13.31	6.81	20
1982	12.08	9.153	51	8.21	4.43	13 <sup>c</sup>
1983	1.88	2.357	140	7.11	5.94	59
1984	6.27	7.195	37	9.61	8.14	30
All	4.42	6.319	333	8.386	6.85	122 <sup>c</sup>
<b>Proportion of time at surface, all years</b>						
	0.212			0.131 <sup>c</sup>		

<sup>a</sup> Canadian data are from mid-late summer (Würsig et al. 1984, 1985b).

<sup>b</sup> 'Alaskan' data for late summer and early autumn of 1981-84 are from Fraker et al. (1985), Reeves et al. (1983), and Ljungblad et al. (1984b, 1985b), respectively. A few of these data came from the western part of the Canadian Beaufort Sea."

<sup>c</sup> These corrected values differ from values in Fraker et al. (1985, p. 35) and Richardson et al. (1986b, p. 178), who used apparently erroneous 1982 data derived from Reeves et al. (1984) rather than the apparently correct 1982 data from Reeves et al. (1983).

Again following Magnusson et al. (1978), the probability that a single observer would detect a bowhead or group of bowheads that is at the surface is as follows:

$$p = \frac{S_1 + S_2 + 2B}{2N}$$

or 0.54 for all whales and 0.56 for on-transect whales. Thus, if a single observer is present on one side of the aircraft, the uncorrected number of bowheads seen on-transect by that observer should be divided by 0.56 to allow for animals present at the surface but not detected. If two observers are present on one side, their joint uncorrected count should be divided by 0.82. These correction factors are independent of any correction for submerged whales.

During surveys in the Canadian Beaufort Sea in 1981, a total of 33 different single bowheads or groups of bowheads were sighted on the right side of the aircraft during periods when two observers were observing independently on that side (Davis et al. 1982). Of these, 17 were seen by both observers ( $B = 17$ ), 7 by only the front observer ( $S_1 = 7$ ), and 9 by only the rear observer ( $S_2 = 9$ ). Based on the method of Magnusson et al. (1978), the estimated number of singles or groups present was 36.5. Of these, 33 (90%) were seen by one or both observers. The probability that a single observer would detect a bowhead or group of bowheads that is at the surface was 0.685. Thus, the 1981 data indicated that, with a single observer on one side of the aircraft, the uncorrected number of bowheads seen by that observer should be divided by 0.685 to allow for animals present at the surface but not detected. If two observers are present on one side, their joint uncorrected count should be divided by 0.90.

A somewhat lower proportion of the bowheads that were at the surface were apparently detected during this study (82% with two observers per side; 56% with one) than in the 1981 study (90% and 68.5%). We do not know whether this difference was attributable to sampling error or to differences between observers, between years, or between whale behavior in summer vs. early autumn. Given the small sample sizes, the difference could be attributable to sampling error alone. Davis et al. (1982, p. 49-51) calculated that the standard error of their 0.685 factor for a single observer was  $\pm 0.177$ . Our corresponding factor, 0.560, was within 1 se. of their value, so the difference was not statistically significant. In any case, we use the values obtained in 1985-86 in the following subsection.

Estimated Numbers Present, 1985.--Ideally, the number of whales within the study area can be estimated by applying the two correction factors discussed above to the raw densities, and then multiplying the corrected density by the size of the study area. Because we expected different densities of bowheads in the continental shelf, continental slope, and far offshore parts of the study area, we attempted to derive separate estimates of densities and numbers in each of these three strata.



The **estimates** of densities and numbers of **bowhead** whales present in the study area in 1985 are very uncertain because of the **low** number of **whales** seen. The estimates in Table 35 differ slightly from the preliminary values given in Richardson et al. (1986b, p. 180) because we now use the new correction factors for missed whales (see above). The systematic survey data suggested that there were about 70 bowheads in the southeast part of the study area in early-mid August 1985. This figure is based on the September 1985 correction factor for submerged whales. It may be an overestimate, since previous studies suggest that bowheads are at the surface and detectable a higher proportion of the time in August than in September (Table 33, 34). There were apparently no bowheads in the study area from 21 August to about 10 September 1985. About 90 bowheads were present in mid and late September, and about 50 were present in early-mid October (Table 35E). We emphasize that these figures are approximate. The estimates for early-mid Aug, late Aug-early Sept, mid-late Sept, and early-mid Oct are based on sightings of only 2, 0, 5 and 2 bowheads, respectively!

The rough estimates based on the systematic surveys are consistent with other evidence. Reconnaissance flights detected no bowheads in the study area in the 21 Aug-10 Sept 1985 period, or in October 1985. Reconnaissance flights did detect bowheads in the study area during mid-late September (Fig. 116-118). We saw about 15 bowheads in a concentration north of Kaktovik during a flight on 26 September, and NOSC saw 19 in the same area the next day. These sightings undoubtedly did not account for all bowheads within the concentration area, but may have represented part of the largest concentration within the study area. The concentration was within the one part of the study area where there was considerable open water; we and NOSC searched that area of open water intensively. The sightings of a peak of 15-19 bowheads there are not inconsistent with an estimate of 90 bowheads in the entire study area in late September.

If the average number of bowheads in the study area was 70 whales for 20 days in August, 90 whales for 20 days in September, plus 50 whales for 20 days in October, then total utilization was only 1400 whale-days during August and .2800 whale-days during migration (Sept-Oct). The August figure may be an overestimate, as noted earlier. The Sept-Oct figure is unexpectedly low. If a bowhead swam steadily westward through the study area at a speed of 5 km/h (Koski and Davis 1980), it would require about 24 h to traverse the area. Assuming that the Western Arctic population contains at least 4417 bowheads (I.W.C. 1986, p. 49), a total utilization of about 4400 whale-days would be expected even if no bowheads stopped (or slowed) to feed in the study area. If the population contains as many as 7200 bowheads, as is now believed possible (I.W.C. in press), the minimum total utilization would be expected to be about 7200 whale-days with no lingering to feed. Behavioral observations showed that at least a few bowheads did indeed feed in the study area (see below). Thus, at least some of the 'numbers present' figures in Table 35E are apparently too low.

We suspect that the apparent discrepancy is attributable to a combination of factors:

Table 35. Estimated **densities** and numbers of bowhead whales in the official study area, 1 August-20 October 1985. All densities are numbers per 100 km<sup>2</sup>. Values in parentheses are based on <1000 km<sup>2</sup> of aerial survey coverage. Values in sections B-E differ from those in Richardson et al. (1986b, p. 180) because the new correction factors for missed whales are used here.

	Continent al Shelf (0-200 m deep)	Cent inental Slope (200-2000 m)	Far Off shore (>2000 m)
<b>A. Uncorrected Density</b>			
1-20 Aug	0.073 <sup>a</sup>	0 <sup>a</sup>	(0) <sup>a</sup>
21-30 Aug	0 <sup>a</sup>	0 <sup>a</sup>	(0) <sup>a</sup>
1-6 Sept	0 <sup>a</sup> b	(0) <sup>a</sup>	(0) <sup>a</sup>
8-13 Sept	0.057 <sup>b</sup>	0.04 <sup>b,c</sup>	0 <sup>a</sup>
18-24 Sept	0.062 <sup>b</sup>		
25-29 Sept	0.060 <sup>b</sup>		
1-20 Oct	0.051 <sup>a,d</sup>	0 <sup>a,d</sup>	(0) <sup>a,d</sup>
<b>B. Density (A) Corrected for Unseen Bowheads at the Surface</b>			
1-20 Aug	0.104 <sup>h</sup>	0	(0)
21-30 Aug	0	0	(0)
1-6 Sept	0	(0)	(0)
8-13 Sept	0.070 <sup>i</sup>	0.06 <sup>f</sup>	0
18-24 Sept	0.076 <sup>e</sup>		
25-29 Sept	0.073 <sup>e</sup>		
1-20 Oct	0.073 <sup>g</sup>	0	(0)
<b>C. Density (B) Corrected for Submerged Bowheads<sup>i</sup></b>			
1-20 Aug	0.85	0	(0)
21-30 Aug	0	0	(0)
1-6 Sept	0	(0)	(0)
8-13 Sept	0.87 <sup>j</sup>	0.5	0
18-24 Sept	0.62		
25-29 Sept	0.60		
1-20 Oct	0.60	0	(0)
<b>D. Area (km<sup>2</sup>) within stratum</b>	8440	7589	9441
<b>E. Estimated Number of Bowheads Present (C x D)</b>			
1-20 Aug	72	0	(0)
21-30 Aug	0	0	(0)
1-6 Sept	0	(0)	(0)
8-13 Sept	48 <sup>j</sup>	38	0
18-24 Sept	52		
25-29 Sept	51		
1-20 Oct	51	0	(0)

<sup>a</sup> Based on NOSC's randomized surveys (see Richardson et al. 1986b, p. 172).

<sup>b</sup> Based on this study.

<sup>c</sup> Rough estimate taking off-transect sightings into account.

<sup>d</sup> Based on LGL reconnaissance surveys.

<sup>e</sup> Based on one sighting from a side of the aircraft where there were two observers; therefore the raw density was divided by 0.82 (see text).

<sup>f</sup> Based on two sightings, one sighting from a side of the aircraft where there were two observers and the other when there was only one observer; average correction factor of 0.7 was assumed.

<sup>g</sup> The two whales seen on-transect were seen during LGL surveys with only one observer on each side of the aircraft; however, 65% of the coverage was by NOSC with >2 observers. An average correction factor of 0.7 assumed.

<sup>h</sup> Based on NOSC survey with one observer on one side of aircraft, and one full-time and one part-time observer on other side. An average correction factor of 0.7 is assumed.

<sup>i</sup> Based on Density (B) divided by the 0.122 correction factor from Table 33.

1. We probably overestimated the detectability of bowheads in the study area in 1985. During the periods of September and October when most bowheads traversed the study area, most of the area was >90% ice covered. Bowheads are often difficult to detect in such conditions. Both of the correction factors applied to the raw densities were based primarily on observations of bowheads in open or largely-open water.
2. Some bowheads migrate westward over deep waters beyond the 2000 m contour (Table 30; Ljungblad et al. 1986c). Survey coverage far offshore was meagre in 1985. The failure to detect whales there in 1985 may have been partly attributable to limited survey coverage far offshore as well as the heavy ice conditions after mid September.
3. Some bowheads may not have entered the Canadian Beaufort Sea in the summer of 1985. Despite very wide-ranging surveys, Davis et al. (1986b) could not account for the entire population. In particular, they did not locate many adult bowheads (those >13 m long). If some of these whales remained north or west of the study area all summer, they would not have migrated west through that area in autumn.

Another possibility is that the present population estimates are too high. Both the 4417 and the new 7200 estimate have wide confidence limits (e.g. 95% C.I. of 2613-6221 around the 4417 estimate--I.W.C. 1986).

Estimated Numbers Present, 1986.--The densities and estimated numbers of whales present in 1986 were higher than in 1985 (Table 36 vs. .35). The aerial survey results suggest that about 220-370 whales were present at various times in September. NOSC's results from August suggest that there may have been about 340 bowheads in the study area in mid August, but none in late August. However, the 340 figure is based on limited survey coverage and sightings of only three whales, all very close to the eastern edge of the study area. We believe that 340 is an overestimate of the number present in mid August. The assumed density of whales present in early October is speculative so the estimate of 100 whales present at that time is also very uncertain. There is no information about numbers present in early August or in mid-late October.

If the numbers present were as shown in Table 36E, total utilization of the study area would be 3400 whale-days in August, 8550 whale-days in September, and 1000 whale-days in October--a total of 12950 whale days. Even if the August figure is an overestimate, as we believe, the total for the season apparently exceeded 10000 whale-days. The estimate for the migration period in September-October 1986 is 9550, as compared with 2800 for September-October 1985. If the population contains 4417 whales, then an average whale apparently was in the official study area for at least 2-3 days in August-October 1986. The average would be somewhat higher, perhaps 3-4 days, if some whales were present in early August or in mid-late October, or if the assumed density in early October was too low. If the population size is about 7200 rather than about 4417, then the average bowhead was present for at least  $1\frac{1}{2}$  days, and possibly  $2-2\frac{1}{2}$  days.

**Table 36.** Estimated densities and numbers of bowhead whales in the official study area, 11 August-10 October 1986, All densities are numbers per 100 km<sup>2</sup>. Values in parentheses are based on <1000 km<sup>2</sup> of aerial survey coverage.

	Continental Shelf (0-200 m deep)	Continental Slope (200-2000 m)	Far Offshore (>2000 m)
<b>A. Uncorrected Density</b>			
11-20 Aug	0 <sup>a</sup>	(0.38) <sup>a, i</sup>	(0) <sup>a</sup>
21-31 Aug	0 <sup>a</sup>	0 <sup>a</sup>	(0) <sup>a</sup>
1-10 Sept	0.28 <sup>b, c</sup>	0.12 <sup>b</sup>	0 <sup>a</sup>
11-21 Sept	0.21 <sup>b, c</sup>	0 <sup>b</sup>	(0) <sup>a</sup>
22-30 Sept	0.33 <sup>b, c</sup>	0 <sup>b</sup>	(0) <sup>a</sup>
1-10 Oct	(0.10) <sup>d</sup>	(0) <sup>d</sup>	(0) <sup>d</sup>
<b>B. Density (A) Corrected for Unseen Bowheads at the Surface</b>			
11-20 Aug	0	(0.54) <sup>f, i</sup>	(0)
21-31 Aug	0	0	(0)
1-10 Sept	0.35 <sup>e</sup>	0.15 <sup>e</sup>	0
11-21 Sept	0.30 <sup>f</sup>	0	(0)
22-30 Sept	0.41 <sup>e</sup>	0	(0)
1-10 Oct	(0.15) <sup>d</sup>	(0) <sup>d</sup>	(0) <sup>d</sup>
<b>C. Density (B) Corrected for Submerged Bowheads<sup>g</sup></b>			
11-20 Aug	0 <sup>a</sup>	(4.43) <sup>i</sup>	(0)
21-31 Aug	0 <sup>a</sup>	0	(0)
1-10 Sept	2.87	1.23	0
11-21 Sept	2.46	0	(0)
22-30 Sept	3.36	0	(0)
1-10 Oct	(1.23) <sup>d</sup>	(0) <sup>d</sup>	(0) <sup>d</sup>
<b>D. Area (km<sup>2</sup>) within stratum</b>	<b>7940<sup>c</sup></b>	<b>7589</b>	<b>9441 "</b>
<b>E. Estimated Number of Bowheads Present (C x D)</b>			
11-20 Aug	0	(340) <sup>i</sup>	(0)
21-31 Aug	0	0	(0)
1-10 Sept	230 <sup>c</sup> +50 <sup>h</sup>	90	0
11-21 Sept	200 <sup>c</sup> +20 <sup>h</sup>	0	(0)
22-30 Sept	270 <sup>c</sup> +0 <sup>h</sup>	0	(0)
1-10 Oct	(100) <sup>d</sup>	(0) <sup>d</sup>	(0) <sup>d</sup>

<sup>a</sup> Based on NOSC's randomized surveys (Table 31).

<sup>b</sup> Based on this study (Table 29) plus NOSC's randomized surveys (Table- 31).

<sup>c</sup> Excluding 10 km x 50 km feeding area off Kongakut Delta and Demarcation Bay (see text).

<sup>d</sup> Rough estimates; data are inadequate or lacking.

<sup>e</sup> Based partly on LGL surveys with two observers on each side of aircraft, and partly on NOSC surveys with an observer plus part-time observer and/or pilot on each side. Therefore, raw density was divided by 0.8.

<sup>f</sup> Based on either NOSC surveys as in footnote<sup>e</sup>, or NOSC surveys plus LGL surveys with two observers on one aide and an observer plus pilot-observer on the other aide. Raw density was divided by 0.7.

<sup>g</sup> Based on Density (B) divided by the 0.122 correction factor from Table 33F.

<sup>h</sup> Estimated number in 10 km x 50 km feeding area off Kongakut Delta and Demarcation Bay, based on Fig. 127 with allowance for missed whales.

<sup>i</sup> Probably an overestimate -- see text.

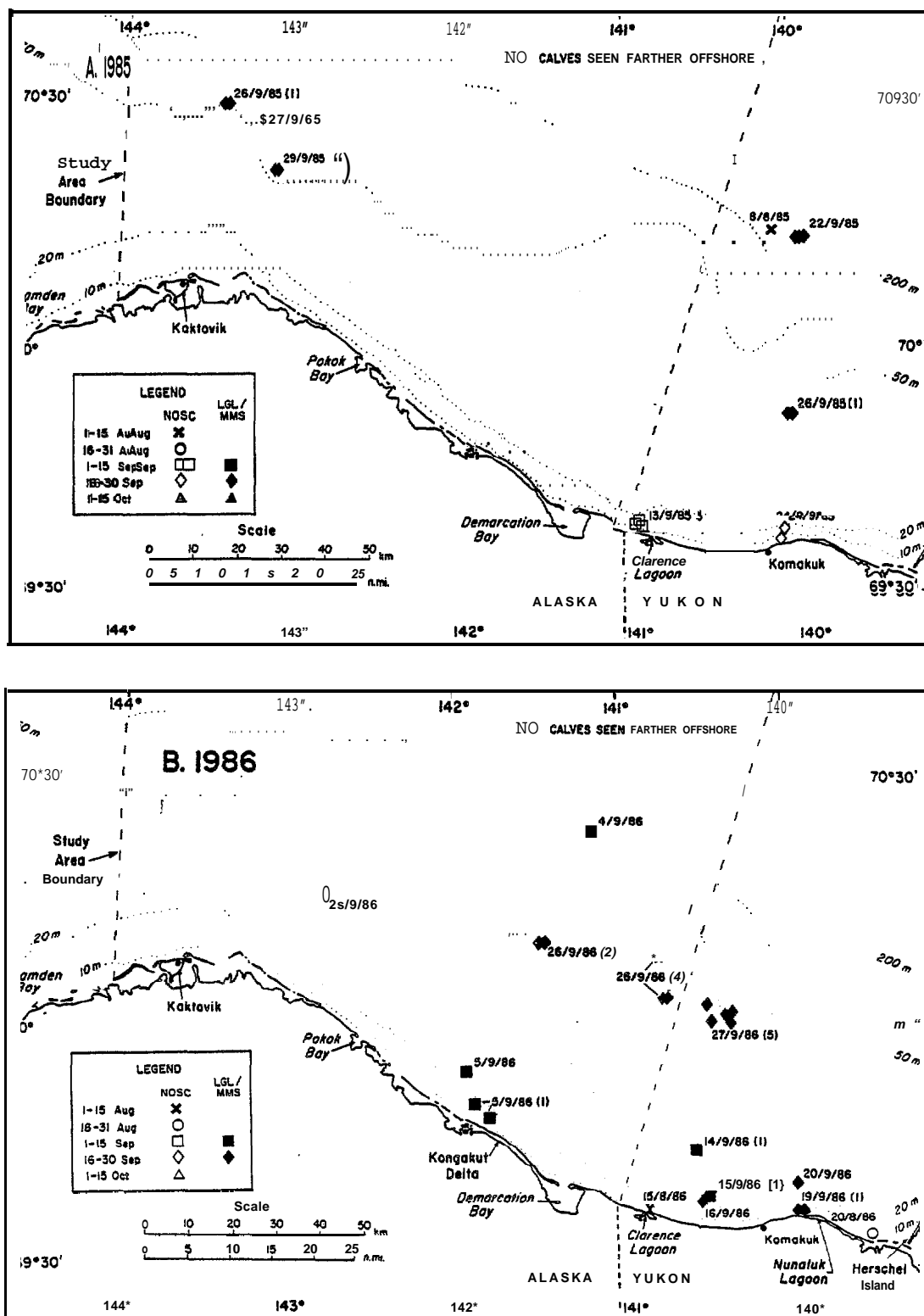
These estimates of utilization of the official study area during August-October 1986 exceed the <1 day figure for the corresponding period of 1985. As noted earlier, the 1985 figure was probably underestimated because of the heavy ice cover and low detectability of whales after mid September 1985. Whale detectability was better in 1986 than in 1985 because ice was virtually absent throughout the 1986 survey period, and because the weather and sea conditions were unusually favorable in 1986. Thus, the calculated whale-days values for 1985 probably were underestimates, whereas the values for 1986 probably were more accurate. As a result, utilization of the study area by bowheads may have been more similar in 1986 and 1985 than is suggested by the whale-days figures. Nonetheless, utilization of the study area by feeding whales was clearly greater in 1986 than in 1985. Whales fed in the nearshore portion of the official study area in early September 1986, whereas this did not happen in 1985.

#### Presence of Mothers and Calves in the Study Area

In 1985, bowhead calves were present in two and possibly all three of the areas where significant numbers of older bowheads were detected (Fig. 129A). In late September of 1985, we saw calves far offshore from Komakuk and Kaktovik. We did not see calves amidst the many whales close to shore near Komakuk. Our photogrammetry in the Komakuk area also showed no calves and very few animals large enough to be mothers (see Fig. 130 on p. 313). However, Ljungblad et al. (1986c, p. C-7) reported visual sightings of a total of five calves in the Komakuk area on 13 and 24 September 1985 (Fig. 129A). On 13 September, we photographed and measured 15 different whales at the location where Ljungblad et al. reported three calves on the same date. Two probable yearlings 7.0 and 7.4 m in length and one adult-sized whale (13.0 m) were present, but we found no calves and no other potential mothers.

In total, of the 199 bowheads that we saw in and near the official study area during 1985, 9 (4½%) were calves. We and NOSC saw more calves in late September (14) than in early September (3) (Table 37). Within the official study area, 4 of 47 bowheads seen by us (8½%) were calves. Late September was the only period when significant numbers of either calves or older whales were detected in the official study area.

In 1986, bowhead calves were present in each of the areas where significant numbers of older bowheads were found--along the Yukon coast near Komakuk, along the Alaskan coast near the Kongakut Delta, and offshore in the mid and outer shelf regions (Fig. 129B). We saw a total of 21 calves in September 1986, of which 10 were in the official study area. (We do not express these values as percentages of total number of bowheads present because the latter could not always be estimated accurately in areas where many whales were feeding.) NOSC saw three calves in the area that we map, of which one was in the official study area. On one occasion, 27 September, the photogrammetric work confirmed that there were at least five different calves amidst one concentration of whales; they were near the 50 m contour just east of the official study area (Fig. 12913). Significant numbers of calves (and larger whales) were in the official study area in early September 1986--earlier than in 1985 (Table 37).



**FIGURE 129.** Locations where bowhead calves were seen by ourselves and Naval Ocean Systems Center during the period 1 August to 15 October in (A) 1985 and (B) 1986. NOSC data for 1985 and 1986 are from Ljungblad et al. (1986c, in prep.). For each visual sighting, the date is given as day/mo/yr, followed in parentheses by the number of calves confirmed by photogrammetry. Note: Fig. 129A follows Ljungblad et al. (1986c, p. c-7) in showing three calves at Clarence Lagoon on 13 Sept 1985; preliminary NOSC data quoted by Richardson et al. (1986b, p. 181-184) showed only two.

The calves seen in both years were usually in very **close** association with **large** adults, almost certainly their mothers. Occasionally we saw calves **diving** under the genital region of the associated **adult** in order to nurse, as described by Würsig et al. (1985a). Thus, calves seen **in** the groups **of** feeding whales present **along** the coast in September 1986 were obtaining their nourishment from **their mothers**, which were **in turn** feeding in the coastal waters near the **Kongakut Delta** and **Komakuk**.

The pattern **of** sightings of cow-calf pairs **in** 1985-86 was generally consistent **with** that **in** earlier years. Over the 1979-86 period as a whole, both cow-calf **pairs** and other **whales** have been seen from early August to October, with a peak **in late** September (Table 38). Numerous cow-calf pairs have been seen in 'both the continental shelf zone (depths 0-200 **m**) and the continental slope zone (200-2000 **m**). Furthermore, two **of** the few whales seen **in water** deeper than 2000 m were also calves. Cow-calf sightings, like other sightings, tended to be farther offshore before **than after** 15 September (Table 38).

#### Length Measurements\*

**Usable** length measurements (grades 1 to 6) were obtained from 189 whale images in 1985 and 218 whale images in 1986. Of these, 70 and 47 measurements, **respectively**, were repeats of previously measured whales. Hence 119 and 171 different **whales** were measured in 1985 and 1986, respectively. **In the** following sections, **only** one measurement of "each **whale is** included in each frequency distribution. When a **whale** was photographed on **different days**, it is included in each of the **daily** frequency **distributions**, but **only** once in the combined data for the **area**.

Each location where whales were photographed is shown by an X in Figure 111 (p. 267). At most of these locations, whales were photographed immediately after a behavioral observation session. **However**, the photo session often covered **a** somewhat larger area than the associated behavioral **observations**, i.e. some **photo** sessions included whales that were not observed **in detail** during the preceding behavioral observations. For purposes of comparison, whale measurements have been summarized for five areas where we found whales.

Whales less than about 7 m **long** in **late** summer are generally calves <1 year **old**; some calves may be as much as 7.5 m **long** in September. Whales over 13 m **long** are considered to be **mature adults** (Davis et al. 1983, 1986a,b; Nerini et al. 1984, 1987). Intermediate-sized animals (age >1 year but **not** mature) are referred to as **subadults** in this report.

Nearshore Komakuk, 1985-86. --Whales were measured from photographs taken **along the** Yukon coast near **Komakuk** on five dates **in** 1985 (28 Aug and 8 Sept from Davis et al. 1986b; 11, 13 and 24 Sept from this study) and **on** seven dates **in** 1986 (Fig. 131; **this study**). Almost **all whales** photographed near **Komakuk** were in water <25 m deep, and <15 km from shore (Fig. 111 on p. 267). These **whales** did **not** show strong directional movement. They were predominantly **subadult whales**, many of which 'were <10 m long (Fig. 130A,B, 131A, 132A). Of the 106 different whales measured there in 1985, 47% were **small subadults** (non

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\* Prepared by William R. Koski, LGL Ltd.

Table 37. Number of bowhead calves seen in and near the official study area, 1985-86, during (1) the present LGL study and (2) the Naval Ocean systems Center study.

Depth	1-15 Aug	16-31 Aug	1-3.5 Sep	16-31 Sep	1-15 Oct	Total
<b>Within Area Mapped<sup>a</sup></b>						
1985- LGL	-		0	9	0	9
- NOSC <sup>b</sup>	1	0	37 <sup>c</sup>	5	0	9
- Total	1	0	37 <sup>c</sup>	14	0	-E'-
1986 - LGL		-	6	15		21
- NOSC	1	1	0	1	0	3
- Total	1	- i -	6	16	0	24
<b>Official Study Area<sup>d</sup></b>						
1985- LGL			0	4	0	4
- NOSC	0	0	0	3	0	3
- Total	0	0	0	7	0	7
1986- LGL			4	6		10
- NOSC	0	0	0	1	0	1
- Total "	0	0	4	7	0	11

<sup>a</sup> Longitudes approximately 139° to 145° (Fig. 129).

<sup>b</sup> NOSC data are from Ljungblad et al. (1986c) for 1985 and J. Clarke and D. Ljungblad (pers. comm.) for 1986.

<sup>c</sup> See text for a discussion of these three putative calves.

<sup>d</sup> Area bordered by dashed lines on Figure 129.

Table 38. Number of bowhead calves seen within the official study area in 1979 through 1986 according to date and depth stratum<sup>a</sup>. There were no calf sightings in 1980 or 1981.

Depth	1-15 Aug	16-31 Aug	1-15 Sep	16-30 Sep	1-15 Oct	Total
>2000 m	0	1	1	0	0	2
200-2000 m	3	3	2	0	2	10
<200 m	2	0	5	24	1	32
All Depths	5	4	8	24	3	44

<sup>a</sup> Data for 1979-84 were compiled by McLaren and Richardson (1985) from NOSC data (Ljungblad et al. 1980-85b) and LGL data (Johnson 1984; unpubl. 1984 data). Data for 1985-86 are from this study, Ljungblad et al. (1986c) and J. Clarke and D. Ljungblad (pers. comm.) ).



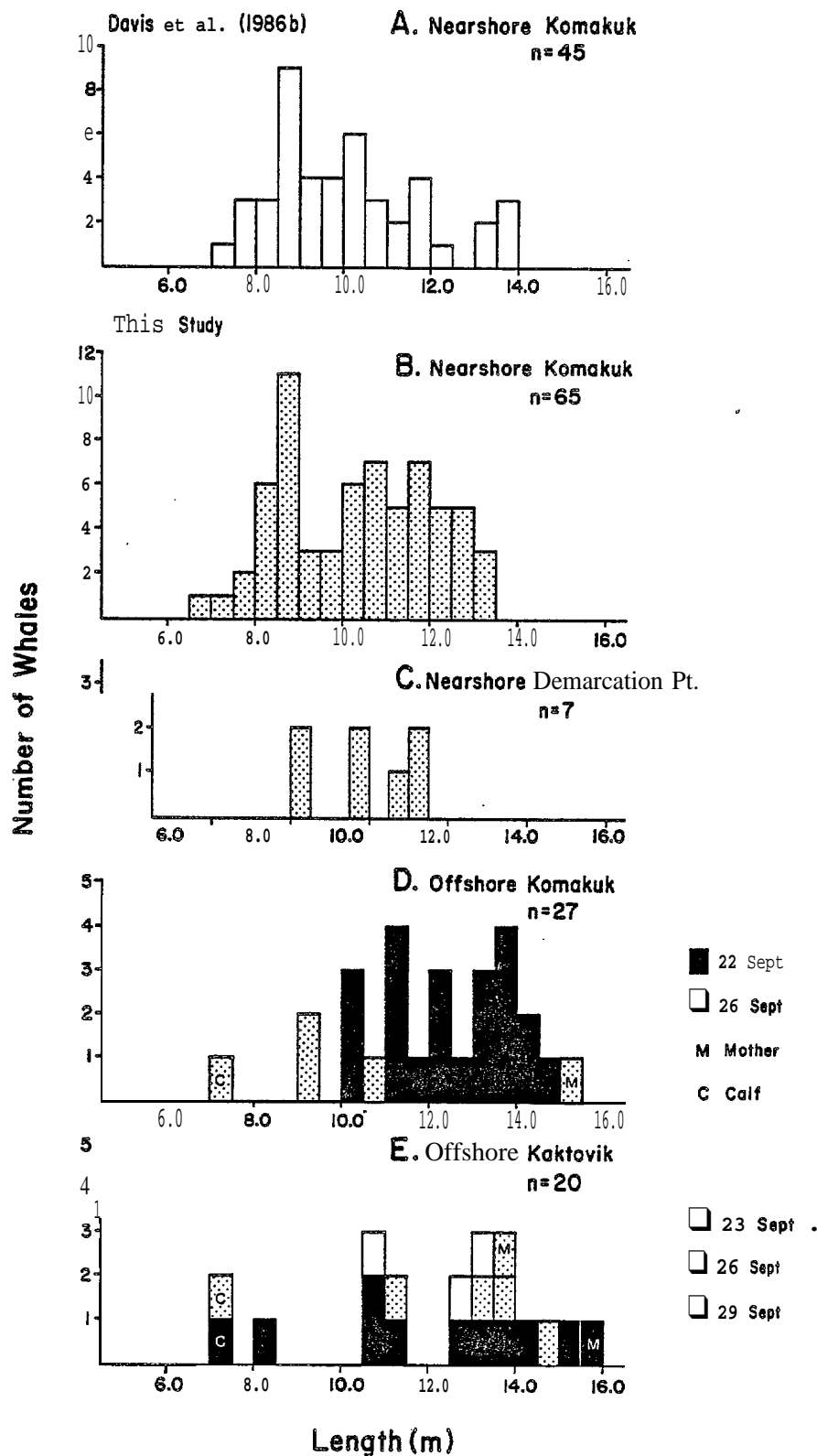
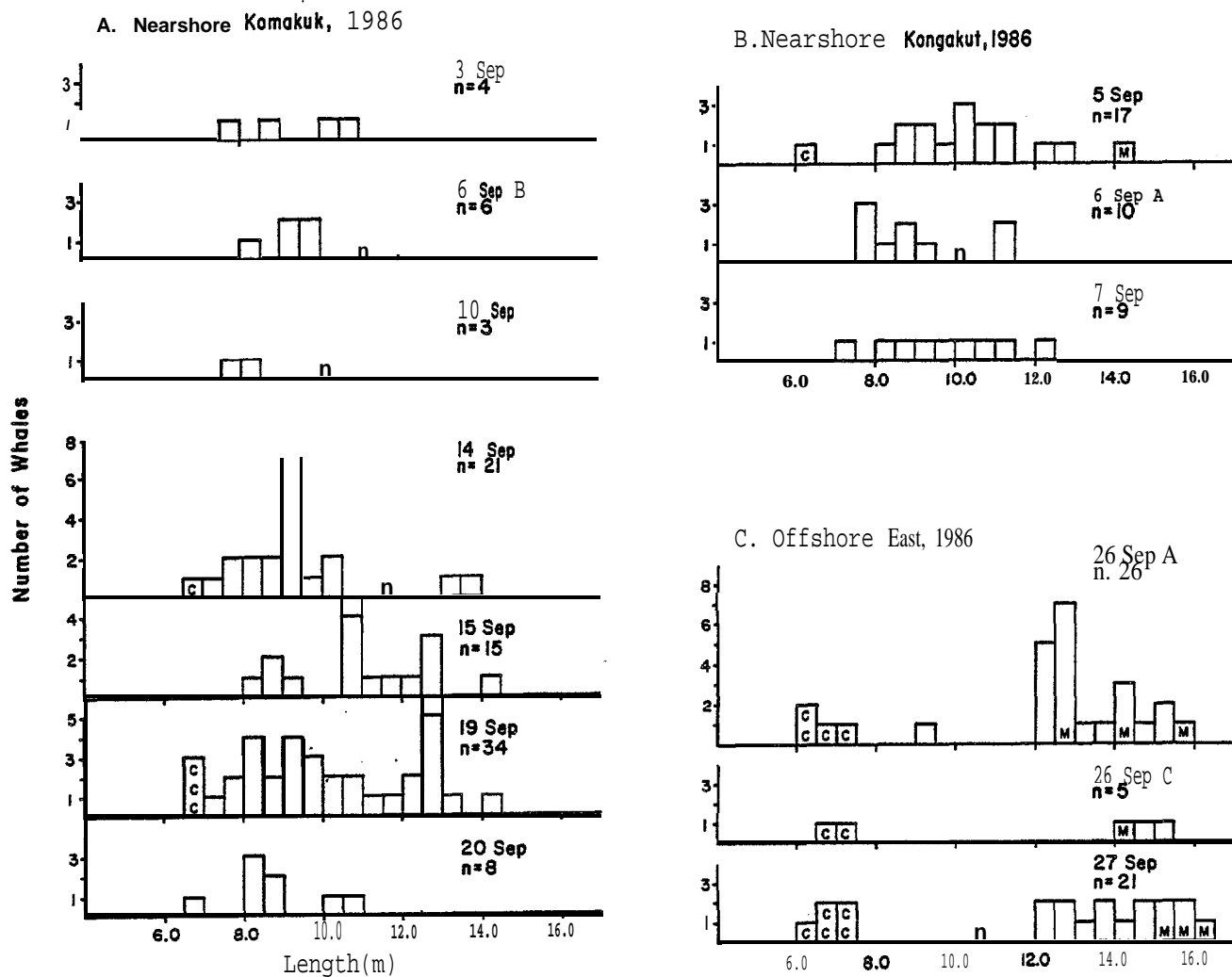


FIGURE 130. Pooled length-frequency distributions of bowheads photographed in and near the official study area in 1985 by ourselves and Davis et al. (1986b). Data are from 28 August-29 September 1985. See Richardson et al. (1986b, p. 186) for daily results from the Komakuk area. Within- and between-day repeats are excluded.



**FIGURE 131.** Daily length-frequency distributions for bowheads photographed in three areas during this study, 3-27 September 1986. Within-day repeats are excluded.

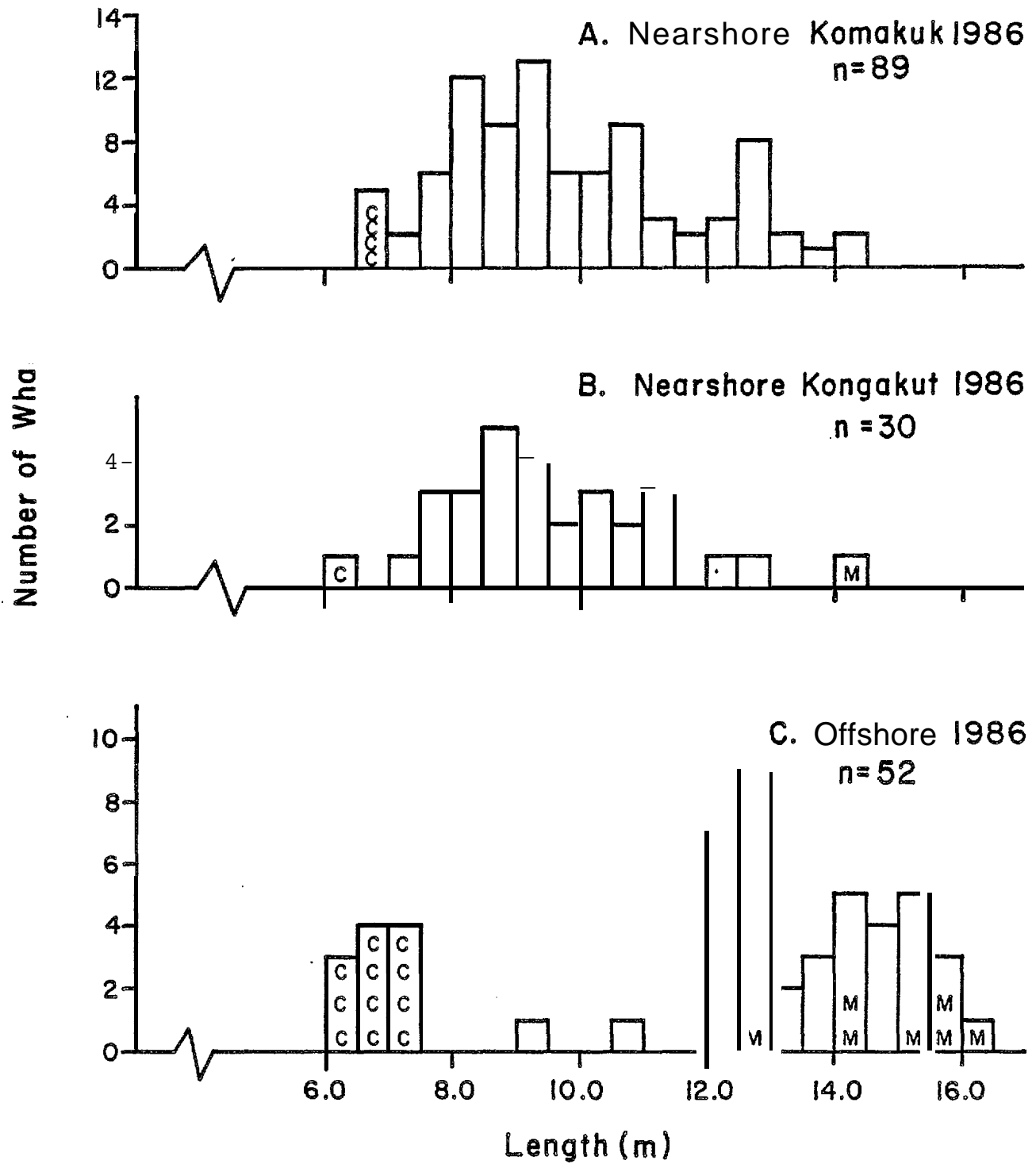


FIGURE 132. Pooled length-frequency distributions of bowheads photographed in three areas during this study, 3-27 September 1986. Within- and between-day repeats are excluded.

calves <10.0 m), another 47% were larger **subadults**, and only 6% were adults (Table 39). Similarly, 55% of the 89 different whales measured in this area in 1986 were small **subadults**, 35% were larger **subadults**, and only 6% were **adults** (Table 39). The size distribution near **Komakuk** was relatively constant throughout the periods when whales were photographed in this area--late August to late September in 1985 (Richardson et al. 1986b, p. 186), and **early to late** September in 1986 (Fig. 131A).

In 1986, unlike 1985, a few **calves** were photographed in nearshore waters off **Komakuk**. In 1985, none of the **small** whales photographed there were believed to be calves, although one apparent yearling from 13 September was only 7.0 m long. As noted **earlier**, we did not recognize any of the **small** whales seen **visually** near **Komakuk** in 1985 as calves, although Ljungblad et al. (1986c) reported visual observations of **calves** there on two dates, including 13 September (Fig. 129A). In 1986, in contrast, four calves (4%) photographed in this area ranged in length from 6.6 to 6.9 m. An additional whale slightly smaller than 7.0 m was believed to be a yearling. There were several visual sightings of **calves** near **Komakuk** in 1986 (Fig. 129B).

Bowheads were also present **along** the Yukon coast near **Komakuk** in late summer of 1984. In 1984, like 1985 and 1986, most bowheads **near Komakuk** were subadults (mainly 8-11 m); 74% of the whales measured from this area in 1984 were subadults <10.0 m long (Table 39). However, a 13.8 m mother and 5.8 m **calf** were found here on 18 August 1984 (Davis et al. 1986a). In 1983-85, the large numbers of bowheads farther east along the Yukon coast, i.e. southeast of Herschel Island in Mackenzie Bay, were also predominantly **subadults** (Würsig et al. 1985b; Davis et al. 1986a,b).

Nearshore Kongakut Delta, 1986.--Whales were photographed in nearshore waters within the southeastern part of the official study area, off the **Kongakut** River Delta, on three occasions in 1986 (5, 6 and 7 Sept; Fig. 111B on p. 267). The sizes of **whales** photographed here were similar to those farther east in nearshore waters off **Komakuk** (Fig. 131A,B, 132A,B). Of the 30 measured whales, the majority (60%) were **small subadults** (Table 39). The **single large whale** (14.0 m) was a cow with a 6.3 m **calf**.

Migrants Near Demarcation Point, 1985.--A **loose** group of about 8-10 bowheads was photographed on 19 September 1985 as they were migrating rapidly westward parallel to the coast in about 13 m of water (Fig. 111A). This group was slightly west of the whales near **Komakuk**, but appeared to be coming from **that area**. Because of its migratory behavior, this group was considered separately. The seven measured whales were 8.2-11.2 m long (Fig. 130C). Although one possible **calf** was identified during behavioral observations that preceded this photo session, neither a calf nor an **adult large** enough to be a mother was measured.

Offshore near Eastern Edge of Study Area, 1985-86.--In 1985, **whales** were photographed about 70 and 35 km offshore from **Komakuk** on 22 and 26 September. Water depths were about 280 m and 40 m, respectively. In 1986, **whales** were photographed at two offshore locations on 26 September and one on 27 September. All three 1986 locations were about 50 km offshore and in water about 45 m deep. Three of these five sessions were just east of the official study area and two were inside the eastern part of that area (Fig. 111).

Table 39. Numbers of whales of various sizes measured from photograph taken in and near the official study area, 1984-86. Whales photographed more than once in a given area and year are counted only once.

Area, Year, (No. of photo sessions)	calves	Small Subadults ( $<10.0$ m)	Large Subadults (10-12.9 m)	Adults ( $\geq 13.0$ m)			Overall Total
				Mothers	Others	Total	
Nearshore Komakuk, Yukon							
1984 (3) <sup>a</sup>	1	20	5	1	0	1	27
1985 (7) <sup>b</sup>	0	50	50	0	6	6	106
1986 (7) <sup>c</sup>	4	49	31	0	5	5	89
Nearshore Kongakut Delta							
1986 (3) <sup>c</sup>	1	18	10	1	0	1	30
Nearshore Demarcation Pt.							
1985 (1) <sup>c</sup>	—	4	3	—			7
Offshore — East							
1985 (2) <sup>c</sup>	1	2	13	1	10	11	27
1986 (3) <sup>c</sup>	11	1	16 <sup>d</sup>	7 <sup>d</sup>	17	24	52
Offshore from Kaktovik							
1985 (3) <sup>c</sup>	2	1	7	2	8	10	20

<sup>a</sup> The 1984 data are from Davis et al. (1986a).

<sup>b</sup> Includes data of Davis et al. (1986b) from Komakuk area as well as our data.

<sup>c</sup> Data are all from this study.

<sup>d</sup> A 12.8-m Mother is counted as an Adult.

The size distribution of these offshore **whales** was quite different from that of whales in shallow water. **Adult-sized** whales comprised a much higher percentage of the whales in offshore waters (Fig. 1301), **131C, 132C**). Only **7%** of the 27 whales measured in the eastern offshore area in 1985 were small **subadults** and 41% were adults (Table 39). Similarly, in 1986, only 2% of 52 measured **whales** were small **subadults** and 46% were adults. A substantial proportion of the large whales in this area were accompanied by calves. One 15.2 m **adult** was photographed here with a 7.1 m **calf** on 26 September 1985, and three calves were seen but not measured on 22 September 1985. In 1986, 21% of the measured whales in this area (**11** of 52) were calves. These calves averaged **6.8 m** in **length** (range = 6.1-7.4 m). The seven measured mothers from this area averaged 14.9 m long (range = **12.8-16.1 m**).

Offshore from Kaktovik, 1985. --The whales photographed in this area on 23-29 September 1985 were in 40-50 m of water over 30 km from the Alaskan coast (Fig. 111A). The size distribution was similar to that in offshore waters near the east edge of the study area, and quite different than that in nearshore areas (Fig. **130E**). Of the 20 measured whales, 50% were adults, and only 5% (one whale) were **small** subadults (Table 39). Two small whales, both 7.3 m **long**, were identified as calves although neither was in the same photo as its mother. Two mothers photographed here were **13.7** and 15.6 m long. The latter animal was the largest individual measured during 1985.

Summary. --**Subadults** comprised most of the bowheads feeding **along** the Alaska and Yukon coasts in or just east of the official study area during the **late** summers of 1985 and 1986. About **half** were **<10.0 m long**. In 1985, no calves were identified in nearshore areas near **Komakuk** during **our** study; in **1986**, 4% of the measured whales in nearshore areas (5 of 119) were calves. In contrast, adults and calves were proportionately more common and **subadults** less so in offshore waters during late September of both years. Calves constituted 6% and 21.% of the measured whales in offshore waters during 1985 and **1986**, respectively (**3** of 47 and **11** of 52). The 21% **figure** is the highest relative abundance of calves that has been recorded for any area where extensive length **data** have been collected.

#### Within-Year **Resightings** and Residence Times

Besides providing data on sizes of whales using different parts of the study area, the photogrammetry was designed to document residence times of individually-recognizable whales in various feeding areas. Information on residence times was obtained in both years. In addition, by comparing our photos with those from other LGL projects in the Canadian and Alaskan **Beaufort** Sea, we documented several long-distance within-season movements and several between-year **resightings**.

In **1985**, we acquired a total of 212 potentially re-identifiable (grade A and B) photos of bowheads during 10 photo sessions. Of these, 91 photos represented whales photographed only once insofar as we could determine, whereas **121** photos were of 43 individual **whales** that were photographed 2-5 times within one session ('within-day repeats'). The numbers of whales photographed once, twice, . . . five times during **the** 1985 photo sessions **totalled** 91, 25, **13**, 3 and 4, respectively (Richardson et al. **1986b**, p. 189). This section deals only with the smaller number of 'between-day repeats'. Two

whales were photographed on two different dates during our 1985 work. Also, 11 of the whales photographed by us had been photographed earlier in 1985 during the more extensive photogrammetric study of Davis et al. (1986b). Three more whales in our area were photographed on more than one day by Davis et al. (1986b) but not by us. In total, 16 whales were photographed on two or more days in 1985, including at least one date when the whale was in our extended study area (139°-145°W). (This total excludes the many whales photographed on >1 d by Davis et al. [1986b] in areas east of our study area.) These 16 between-day repeats are mapped in Figure 133, and more details about them are given in Richardson et al. (1986b, p. 190).

In 1986, we obtained 291 re-identifiable (grade A and B) photos of bowheads representing a maximum of 223 different whales. Most of these whales (192) were photographed only once, but 41 individuals were photographed 2-6 times within particular photo sessions, and eight were photographed on more than one day in 1986 (Table 40). One of these eight whales, plus four others that we photographed on only one day, were also photographed on different days by Koski and Johnson (in prep.), who worked simultaneously with us within and west of our study area. Considering both 1986 studies, 12 whales were photographed on two or three different dates (Table 41).

The radio-tagging program was also designed to determine residence times and movement patterns of individual bowheads. Five bowheads were tagged during the 1986 phase of this study, and three of these were relocated at different locations on subsequent days. Appendix 4 gives a detailed account of the radio-tagging work; the results are summarized briefly in the 'Nearshore Komakuk' section, below.

Nearshore Komakuk, 1985-86--Photogrammetry.--In 1985, we photographed bowheads along the Yukon coast near Komakuk on 11, 13 and 24 September (Fig. 111A). During these sessions we obtained 97 grade A and B images representing a maximum of 73 individuals that were potentially recognizable in other photo sessions within 1985. Two of these whales were photographed within the same general area on different dates (11 Sept-13 Sept and 13 Sept-24 Sept; Fig. 133). In addition, four whales photographed by Davis et al. (1986b) during their three photo sessions near Komakuk (14 and 28 Aug; 8 Sept) were later re-photographed in the same general area during this study. One of these whales was photographed on three different dates (28 Aug-8 Sept-13 Sept); the other three were photographed on two dates (8-11, 8-11, and 8-13 Sept). Furthermore, another whale was photographed twice in the Komakuk area by Davis et al. (28 Aug-8 Sept).

Overall, seven bowheads were photographed near Komakuk on two or more dates in 1985 (Fig. 133). The periods between successive resightings ranged from 2 to 11 d, averaging 6.4 d (n = 8). The periods between first and last sightings were 2 to 16 d, averaging 7.3 d (n = 7). Net distances travelled between successive resightings were 2 to 24 km, averaging 10.3 km or 1.6 km/day. Net movements in the Komakuk area were small but mainly easterly (6 of 8 resightings). The cluster of resightings in the Komakuk area shows that this area was occupied at least intermittently by some of the same individual bowheads during late August and September of 1985.

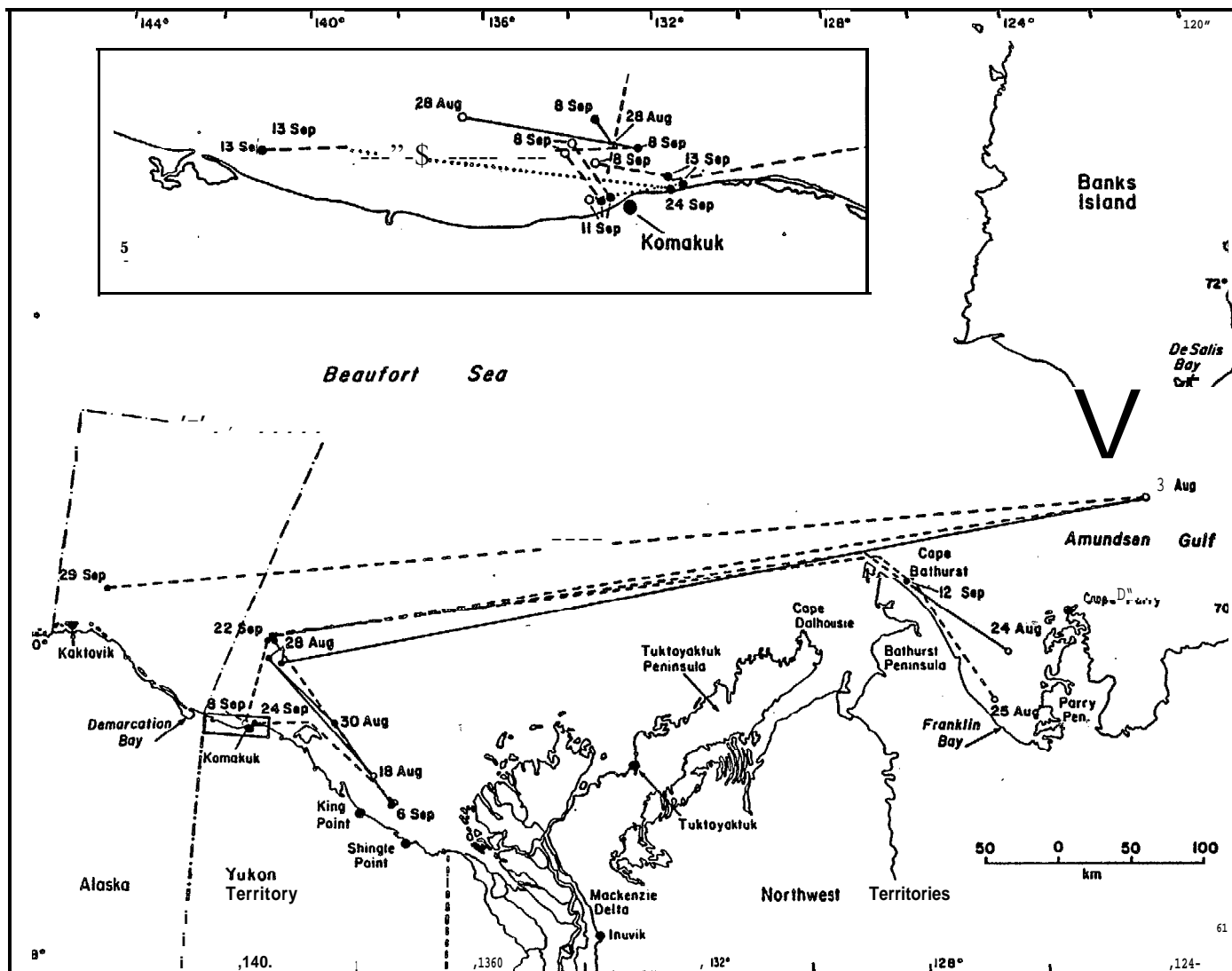


FIGURE 133. Inter-clay resightings of bowheads photographed in or near the MMS study area, 1985. Open circles indicate the locations of the original photographs; closed circles indicate the resightings. Solid lines connect resightings by Davis et al. (1986b), dotted lines connect resightings within this study, and dashed lines connect between-project resightings.



Table 40. Number of photographs of recognizable bowhead ties acquired during 1986 photo sessions. See Richardson et al. (1986b, p. 189) for comparable summary of 1985 photo sessions.

Photo Session	Number of Whale Images		Number of Whales Photographed 1,2,...,6 times						No. Whales Potentially Recognizable Between Days <sup>a</sup>	Number of Inter-day Re-identifications with Whale Photographed During	
	Printed	Grades A & B	1	2	3	4	5	6		This Study	Other Study
Konakuk											
3 Sep	5	3	3						3		
6 Sep (B) <sup>c</sup>	11	11	6	1	1				8	1 (14 Sep)	1 (5 Sep)
10 Sep	10	8	8						8		
14 Sep	38	36	32	2					34	1 (15 Sep), (6 Sep)	1 (5 Sep)
15 Sep	30	28	22	3					25	(14 Sep)	
19 Sep	46	45	38	2	1				41		1 (5 Sep)
20 Sep	11	11	11						11		
Kongakut Delta											
5 Sep	32	31	12	6	1	1			20	6 (6, 7 Sep)	
6 Sep (A) <sup>c</sup>	18	18	12	0	2				14	(5 Sep)	
7 Sep	13	13	11	1					12	(5 Sep)	
Offshore											
26 Sep (A) <sup>c</sup>	33	30	23	2	1				26		
26 Sep (C) <sup>c</sup>	8	8	5		1				6		
27 Sept	50	49	9	8	3	1	1	1	23		2 (1 Oct)
Total	305	291	1 9	2 2	5 1	0 2	1 1		223 <sup>b</sup>	8	5

<sup>a</sup> These figures are maxima because some repeat photographs may not have been recognized.

<sup>b</sup> This total was reduced by eight to account for inter-session re-identifications.

<sup>c</sup> There were photo sessions at two different locations on each of 6 and 26 September (Fig. 111B).

Table 41. Inter-session resightings of bowheads in and near the MS study area, September and October 1986. See Richardson et al. (1986, p. 190) for comparable 1985 data. .

Source of Photos <sup>a</sup>	First Photographed				Resighting(s)				Days Between Sightings	Net Distance Between Sightings (km)	Whale Length in 1986 (m)
	Date	Loc'n <sup>b</sup>	Latitude	Longitude	Date	Loc'n <sup>b</sup>	Latitude	Longitude			
Yukon Coast near Komakuk											
S-MIS-MS	5 Sep	Kom	69°37.5'N	140°45'W	6 Sep 14 Sep	Kom Kill	69°37.7'N 69°41.5'N	140°47'W 140°25'W	1 8	1 17	9.1
S - MMS	5 Sep	Kom	69°37.9'N	140°50'W	14 Sep	Kom	69°41.5'N	140°26'W	9	17	10.6
S - MMS	5 Sep	Kom	69°37.8'N	140°45'W	19 Sep	Kom	c. 69°37' N	c. 139°55'W	14	c. 32	10.4
MMS - MMS	14 Sep	Kom	69°42.0'N	140°23'W	15 Sep	Kom	69°41.4'N	140°31'W	1	6	12.0
Kongakut Delta											
MMS - MMS	5 Sep	KD	69°50.3'N	141°52'W	6 Sep	KD	69°49.6'N	141°48'W	1	3	11.2
MMS - MMS	5 Sep	KD	69°50.2'N	141°50'W	6 Sep	KD	69°49.6'N	141°51'W	1	1	10.5
MMS - MMS	5 Sep	KD	69°49.7'N	141°49'W	6 Sep	KD	69°49.5'N	141°51'W	1	1	11.2
MMS - MMS	5 Sep	KD	69°49.8'N	141°53'W	7 Sep	KD	69°47.9'N	141°36'W	2	12	11.0
MMS - MMS	5 Sep	KD	69°49.8'N	141°53'W	7 Sep	KD	69°47.0'N	141°34'W	2	13	10.3
MMS - MMS	5 Sep	KD	69°49.4'N	141°50'W	7 Sep	KD	69°47.3'N	141°36'W	2	10	12.0
Offshore											
MMS - s Mother	27 Sep	OK	70°00.8'N	140°22'W	101%	OF	70°16.6'N	145°58'W	4	212	15.5
" Calf	"	"	"	"	"	"	"	"	"	"	6.9

<sup>a</sup> MMS - this study by LGL for MMS. S = 1986 study by LGL for Shell Western Exploration & Production Inc. (Koski and Johnson In prep.).

<sup>b</sup> Locations : KD = Kongakut Delta, Kom = Komakuk, OK = Offshore Komakuk, OF = Offshore from Flaxman Island.

However, there was also some exchange between Komakuk and other areas in 1985. A whale photographed near Komakuk on 8 September was re-photographed 66 km to the north on 22 September (Fig. 133). Other bowheads were still present at Komakuk on the latter date (Fig. 117). Another whale at Komakuk on 24 September had been 123 km to the southeast near King Point on 6 September (Fig. 133). Thus, the composition of the group of whales at Komakuk in September 1985 was not static.

In 1986, we photographed bowheads along the Yukon coast between Clarence Lagoon and Herschel Island on seven occasions from 3 to 20 September (Fig. 111B). We obtained 142 grade A and B images of 128 different whales (Table 40). Seven more grade A and B images of five bowheads were obtained there on 5 and 8 September 1986 during another LGL study (Koski and Johnson in prep.). Four bowheads were photographed in this area on more than one day in September 1986 (Table 41; Fig. 134). The periods between successive re-sightings were 1-14 d, averaging 6.6 d ( $n = 5$ ). Periods between first and last sightings were also 1-14 d, averaging 8.25 d ( $n = 4$ ). Net distances travelled between successive resightings were 1-32 km, averaging 14.6 km ( $n = 5$ ). Apparent rates of movement were very low, 1.0-6.0 km/d, averaging only 2.2 km/d ( $n = 5$ , Table 41). Net movements associated with the longer intervals (8-14 d) were easterly or northeasterly.

Rates of movement and re-sighting intervals in nearshore waters near Komakuk were similar in 1985 and 1986. Combining the data for the two years, there were 13 between-day resightings of 11 different whales. Intervals between successive resightings were 1-14 d, averaging 6.5 d ( $n = 13$ ). Intervals between first and last sightings were 1-16 d, averaging 7.6 d ( $n = 11$ ). Distances between successive locations were 1-32 km, averaging 12 km ( $n = 13$ ). Net rates of movement averaged 1.8 km/d, most commonly to the east.

Nearshore Komakuk, 1986--Radio-Tagging.--Although none of the bowheads photographed near Komakuk in 1986 was subsequently re-identified elsewhere, three whales radio-tagged near Komakuk during this project were detected farther west. Two whales tagged near Komakuk on 18 and 19 September were detected to the northwest, in the official study area, on 22 and 21 September, respectively. A whale tagged near Clarence Lagoon on 15 September was detected passing Point Barrow, over 600 km to the west, on 1 October (see Appendix 4). These radio-tag data confirm that whales moved generally west when they left the Komakuk area. The exact times and routes of departure are not known. However, the approximate dates of departure determined from radio tags are consistent with the disappearance of whales from the Komakuk area between 20 and 22 September (Fig. 127). It should not be assumed that all whales moved directly west when they left the Komakuk area. Short-distance movements within that area were more often east than west in both years. Furthermore, photogrammetry results from 1985 show that one whale moved 66 km north from the Komakuk area to offshore waters between 8 and 22 September 1985 (Fig. 133).

Nearshore Kongakut Delta, 1986.--In 1985 bowheads did not concentrate in this area, but in 1986 we photographed bowheads here on 5, 6 and 7 September (Fig. 111B). We obtained 62 grade A and B images of 40 different whales (Table 40). One more grade B image was obtained here on 4 September by Koski and Johnson (in prep.). Six of the whales photographed here on 5 September were

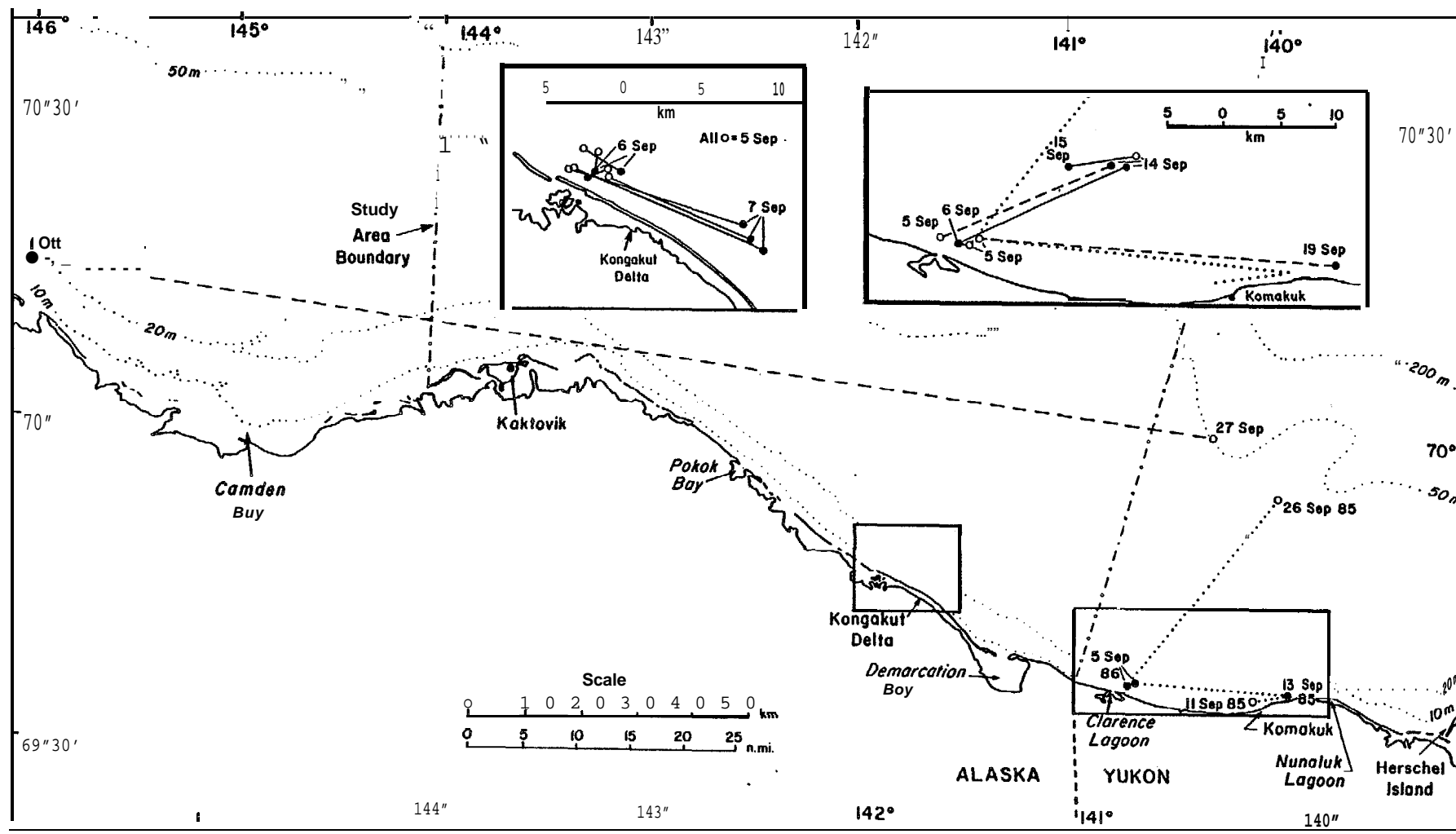


FIGURE 134. Inter-day **resightings** of bowheads photographed in or near the MMS study area, 1986. Open circles indicate the locations of the original photographs; closed circles indicate the **resightings**. Solid lines connect **resightings** within this study, and dashed lines connect **between-project resightings** (cf. Koski and Johnson in prep.). Dotted lines connect 1985 sightings with 1986 inter-day **resightings** of the same whale.

re-photographed in the same general area on the 6th (3 whales.) or 7th (3 whales; Fig. 134; Table 41). The whales had travelled 1-13 km in the 1-2 days between photographs; net rates of movement averaged 4.4 km/d (n = 6, Table 41).

Moderate numbers of whales were observed in the Kongakut Delta-Demarcation Bay area until 10 September 1986, although there were no photo sessions in this area after the 7th. There were few whales along this part of the coast after the 10th, but many whales remained about 25-75 km to the east in the Komakuk area until about 20 September (Fig. 127). Despite good photographic coverage in the Komakuk area until the 20th, none of the whales photographed off the Kongakut Delta on 5-7 September were re-identified near Komakuk. We speculate that they travelled north or west rather than east when they left the Kongakut Delta area..

Migrants Near Demarcation Point, 1985.--As described earlier, whales that were migrating rapidly westward near Demarcation Bay were photographed on 19 September 1985 (Fig. 111A). We obtained 19 images (13 grade A and B) representing a maximum of 10 potentially recognizable whales. None of these migrating whales were photographed during other photo sessions. These whales were apparently migrating westward from the Komakuk area, yet there were no matches with whales photographed earlier in that area.

Offshore In and Near the Study Area---In 1985, aerial surveys indicated that some whales were in the area offshore from Komakuk during August (Fig. 112, 113 on p. 273-274). Two whales photographed there on 28 August by Davis et al. (1986b) had been recorded earlier at very different places: one about 640 km to the east, in Amundsen Gulf, 25 d earlier; and another about 111 km to the southeast, near King Point, 10 d earlier (Fig. 133). Interestingly, the latter whale returned southeastward after 28 August (later sightings not listed in Richardson et al. 1986b). On 30 August this whale was photographed NE of Herschel Island (69°40.2'N, 138°38'W), about 65 km SE of its location off Komakuk on 28 August. By 6 September it had moved 71 km farther southeast to 69°10.2'N, 137°29'W, north of Shingle Point and only 22 km SE of the first location on 18 August.

On 22 and 26 September 1985, we photographed bowheads well offshore from Komakuk (Fig. 111A). Our 63 bowhead images represented as many as 27 recognizable whales. Five whales photographed on the 22nd had been photographed earlier in 1985 by Davis et al. (1986b) (Fig. 133). One had been along the coast near Komakuk on 8 September. Another had been about 112 km to the east, near King Point, on 6 September. Three whales had been photographed about 600 km to the east in Amundsen Gulf and Franklin Bay earlier in the season. One of these had been near Cape Bathurst (473 km to the east) as late as 12 September--only 10 d before we found it off Komakuk.

These sightings suggest that whales offshore from Komakuk on 22 September 1985 had not been there for long, but we have little direct information on their duration of stay. Most were well marked, and many were adults (Fig. 130D). A high percentage (60 of 63, 95%) of the images obtained were considered re-identifiable, but none of these whales were later re-photographed. One distinctively-marked whale photographed on the 22nd may

have moved about 31 km SSW by the next day, based on a probable visual refighting.

We also photographed bowheads farther west, 30-40 km north and northeast of **Kaktovik**, on 23, 26 and 29 September 1985 (Fig. 111A). Bowheads were apparently common in this area from about 22 to 29 September (Fig. 117, 118 on p. 278-279). The 49 images represented up to 26 recognizable individuals. **Only** one of these whales had been photographed earlier in **1985**; a whale photographed on 29 September had been 749 km to the east in **Amundsen Gulf** 57 d earlier (Fig. 133). No whales photographed offshore **from Kaktovik** were **re-photographed** during later sessions (in the case of the 29 Sept photo session, there were no opportunities for **resightings within** this project). These results suggest that the residence **times** of individual whales **off Kaktovik** were brief, and that they were not part of the group of **whales** that had fed near **Komakuk** in late August and much of September."

None of the bowheads that we photographed in 1985 were among 13 whales photographed farther west near **Prudhoe Bay** in September-October 1985 (Johnson *et al.* 1986).

In 1986, we photographed bowheads near the 45 m contour in or near the eastern part of the study area on three occasions on 26 and 27 September (Fig. 111B). We acquired 87 grade A and B images of a maximum of 55 whales (Table 40). There were no between-session **resightings** in this area. However, a cow-calf pair photographed during our last **photo session**, on the 27th, was **re-photographed** by **Koski** and Johnson (in prep.) on 1 October off **Flaxman Island**, west of the study area (Table 41, Fig. 134). This <sup>was</sup> **the only** long-distance movement documented by **photogrammetry** in 1986; this cow-calf pair moved 212 km in 4 d (53 km/d).

There was **only** one refighting in offshore waters of a **bowhead** photographed earlier **close** to shore within the 'extended' study area; this case was in 1985 (Fig. 133). In both years, the **whales** offshore were **mostly larger** than those near the coast (Fig. 130, 132). **These results, plus the** involvement of the offshore **whales in** long-distance **resightings** in both years, suggest that most of **the** whales occurring offshore in **late** September were migrating through the area from locations farther east.

#### Inter-Year Resightings of Identified Individuals

Sixteen bowheads photographed in 1985 and **1986** had **also** been photographed by **LGL** in an earlier year (Table 42). Five whales photographed in 1985 had been photographed in 1984. One of these was also photographed in 1986. Another 11 bowheads photographed in 1986 had been photographed in a prior year (1981, 1982, 1984 or 1985). One additional whale photographed west of the study area in 1986 (**Koski** and Johnson in prep.) had been photographed in **1982** near Herschel Island (Table 42).

Nearshore Komakuk, 1985-86. --Eight bowheads photographed near **Komakuk** in 1985 (2) and 1986 (6) had been photographed in an earlier year (Table 42, Fig. 135, 136). Seven of these eight individuals were **subadults 9.1-12.5 m long**, and were resighted <150 km from where they had been photographed the previous year. These whales were first photographed near **Komakuk** (2), offshore from

Table 42. Between-year resightings, various origins and years, to MMS study area and vicinity, 1985 and 1986. Davis et al. (1986b, p.172) includes 4 of these 1984-85 cases, plus 16 other between-year resightings in the Canadian Beaufort Sea.

Source of Photos <sup>a</sup>	Year	First Photographed				Resighting(s)				Net Distance Between Sightings (km)	Whale Length in Year of Resighting (m)
		Date	Loc'n <sup>b</sup>	Latitude	Longitude	Date	Loc'n <sup>b</sup>	Latitude	Longitude		
Resightings at Komakuk											
DIAND - MMS	1984-85	16 Aug	M S	69°29.3'N	136°48'W	13 Sep	Kom	69°38.0'N	140°40'W	150	12.5
DIAND - MMS		17 Aug	HI	69°39.1'N	139°11'W	13 Sep	Kom	69°37.4'N	140°38'W	54	12.1
DIAND - MMS	1984-86	6 Sep	FB	70°34.8'N	127°18'W	19 Sep	Kom	c. 69°37' N	c. 139°55'W	c. 482	14.2
RP - MMS	1985-86	13 Sep	KYP	69°20.2'N	138°27'W	3 Sep	Kom	c. 69°36' N	139°27'W	c. 64	10.2
MMS - Shell	"	13 Sep	Kom	69°36.5'N	140°02'W	5 Sep	Kom	69°38.0'N	140°44'W	27	10.4
MMS - Shell <sup>c</sup>	"	26 Sep	OK	69°55.1'N	140°03'W	5 Sep	Kom	69°37.5'N	140°45'W	43	9.1
RP - MMS	"	8 Sep	Kom	69°37.5'N	140°13'W	15 Sep	Kom	69°39.0'N	140°29'W	10	10.8
RP - MMS	"	6 Sep	MB	69°09.6'N	137°26'W	19 Sep	Kom	c. 69°37' N	139°55'N	c. 119	10.5
Resightings at Kongakut Delta											
RP - MMS	1985-86	18 Aug	MB	69°20.7'N	137°49'W	5 Sep	KD	69°50.3'N	141°52'W	166	11.0
RP - MMS		13 Sep	KYP	69°26.6'N	138°38'W	5 Sep	KD	69°50.0'N	141°52'W	145	10.8
Resightings Offshore from Komakuk											
DIAND - MMS <sup>d</sup>	1984-85	1 Sep	FB	70°02.2'N	126°52'W	22 Sep	OK	70°13.0'N	139°53'W	518	13.5
DIAND - MMS		14 Sep	Kom	69°35.9'N	140°23'W	22 Sep	OK	70°13.1'N	139°55'N	70	10.2
DIAND - MMS <sup>c</sup>		24 Aug	KP	69°07.9'N	137°37'W	26 Sep	ix	69°55.1' N	140°03'W	132	9.1
SOHIO - MMS	1981-86	24 Jul	AG	71°36'N	124°47'W	27 Sep	OK	69°59.9'N	140°26'W		14.6
MMFS - MMS	1982-86	18 Aug	w i	69°45.8'N	138°47'W	26 Sep	OK	70°03.3'N	140°44'W	80	12.7
RP - MMS	1985-86	21 Aug	AG	70°24.4'N	125°04'W	27 Sep	OK	70°00.4'N	140°26'W	573	15.2
RP - MMS		8 Sep	Kom	69°37.8'N	140°11'W	27 Sep	OK	70°04.7'N	140°38'W	54	13.6
Resightings West of the MMS Study Area											
MMFS - Shell	1982-86	24 Aug	HI	69°40.3'N	138°36'W	19 Sep	O F	70°33.5'N	146°55'W	326	15.4

<sup>a</sup> MMS this study by LGL for MMS. S = 1986 study by LGL for Shell Western Exploration & Production, Inc. (Koski and Johnson in prep.). RP = 1985 reproductive parameters study (Davis et al. 1986b). DIAND = 1984 study by LGL for Canadian Department of Indian Affairs and Northern Development (Davis et al. 1986a). MMS = 1982 study by LGL for U.S. National Marine Fisheries Service (Davis et al. 1983). SOHIO = 1981 study by LGL for Sohio Alaska Petroleum Co. and Others (Davis et al. 1982).

<sup>b</sup> Locations: AG = Amundsen Gulf, N.W.T.; FB = Franklin Bay, N.W.T.; HI = Herschel Island, Yuk.; Kom = Komakuk, Yuk.; KYP = Kay Point, Yuk.; KP = King Point, Yuk.; KD = Kongakut Delta, AK; MB = Mackenzie Bay; OF = Off shore from Flaxman Island, AK; OK = Off shore from Komakuk, Yuk.

<sup>c</sup> Same whale photographed in 1984 (I@), 1985 (OK) and 1986 (Kom).

<sup>d</sup> Also seen in RP study 006 Sept 1985 near King Point (69°10.2'N, 137°29'W).

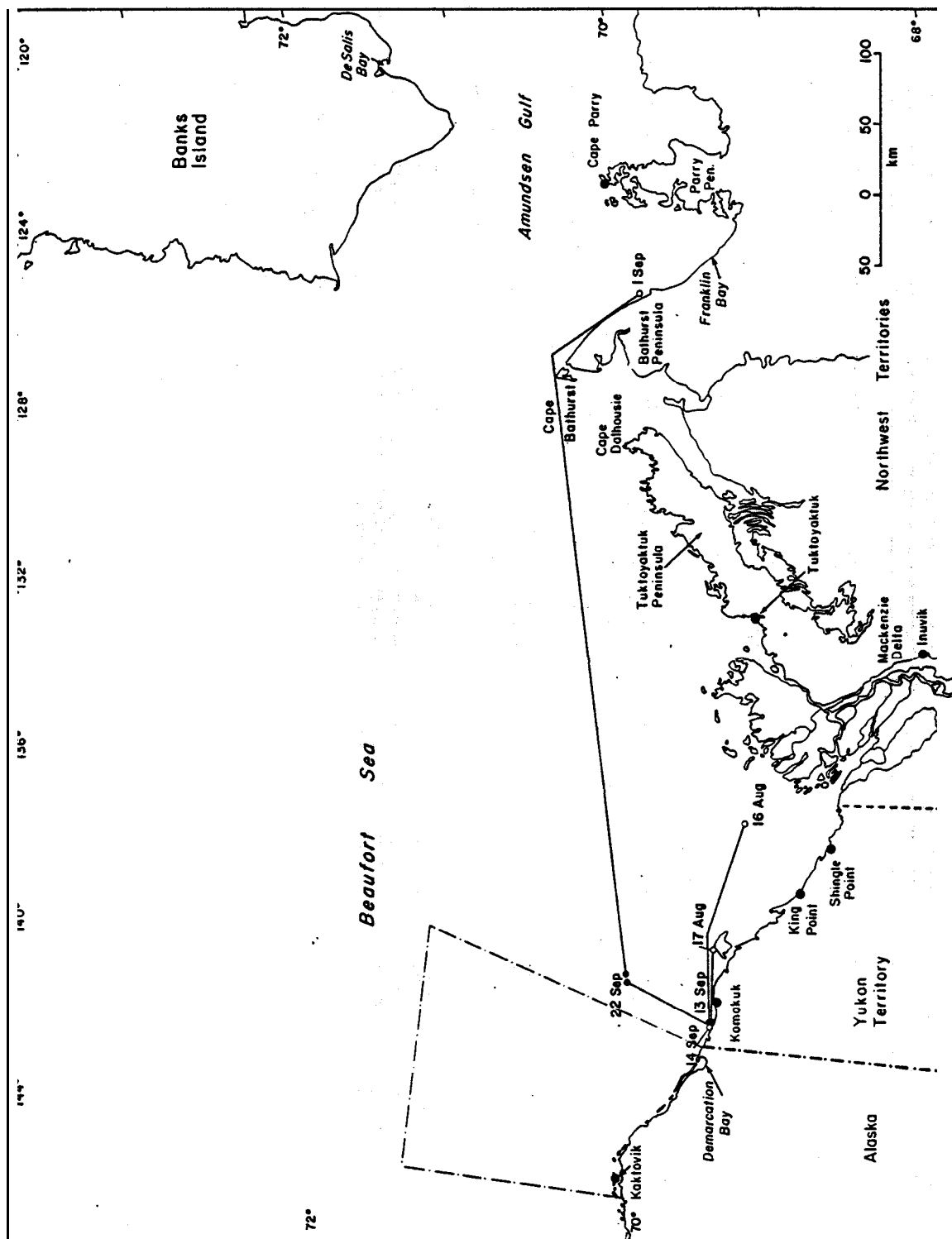


FIGURE 135. Inter-year resightings of bowheads photographed in or near the MMS study area in September 1985. All four whales were first photographed in 1984 by Davis et al. (1986a). See Fig. 136 for one additional whale photographed in 1984, 1985 and 1986.



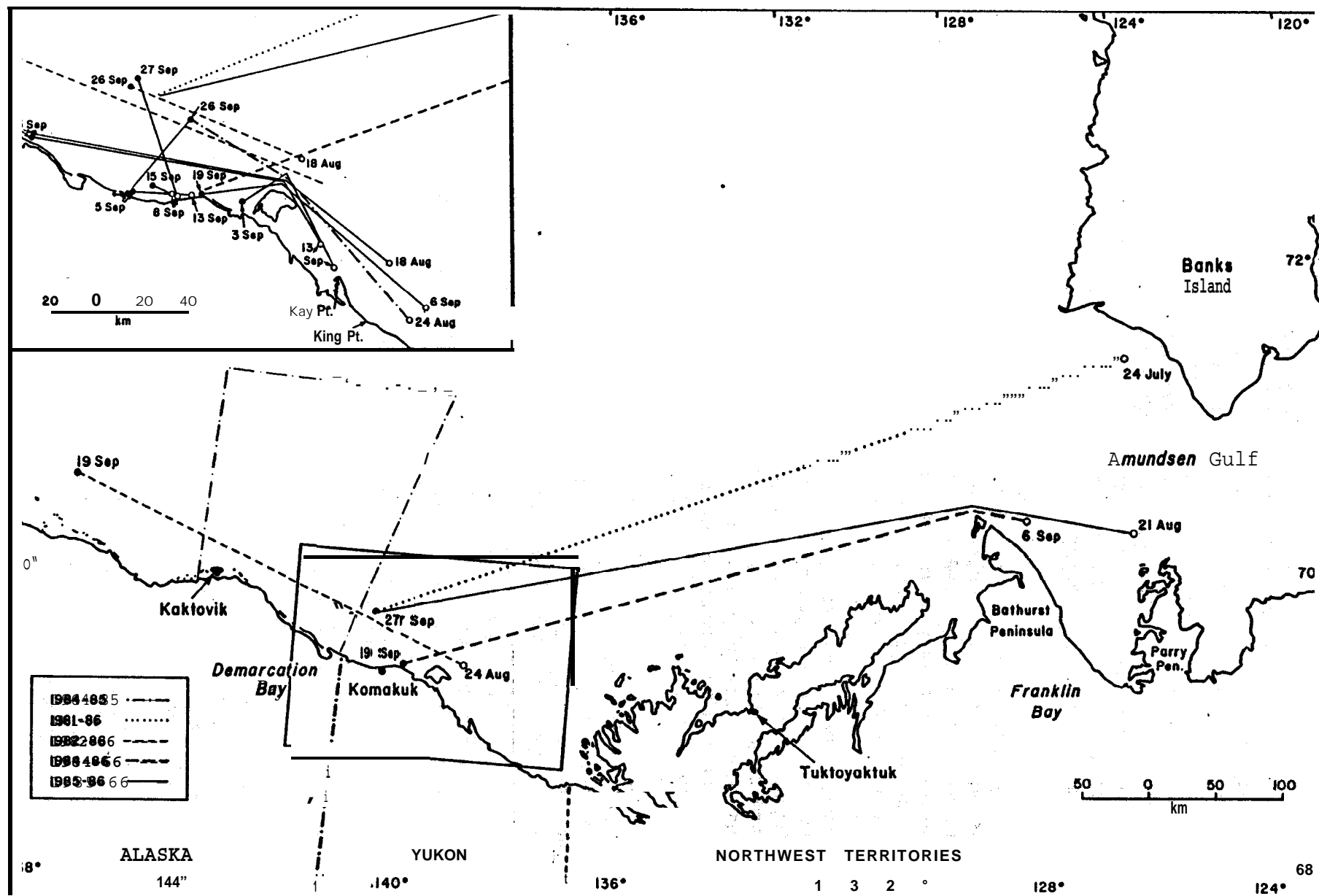


FIGURE 13.6. Inter-year resightings of bowheads photographed in or near the MMS study area in September 1986. The photos from 1981, 1982 and 1984 were by Davis et al. (1982, 1983, 1986a); respectively. The 1985 photos were obtained by Davis et al. (1986b) and this study. The one 1984-85 resighting shown on the inset involved a whale also photographed in 1986; see Fig. 135 for other 1984-85 resightings.

**Komakuk** (1), near Herschel Island (1), in offshore Mackenzie Bay (1), or **along** the eastern Yukon **coast** (2). The eighth whale was a **14.2** m bowhead photographed at Franklin Bay on 6 September 1984, 482 km east of the refighting location near **Komakuk** on 19 September 1986.

The **resightings** near **Komakuk** occurred an average of 6 days ( $n = 8$ ) later in the calendar year than the first sightings (range 21 d before to 28 d after the original sighting **date**). Net distances from sighting to refighting location were 10-482 km, averaging 119 km. All resightings were west of the original locations.

Nearshore Kongakut Delta. --Two **subadult** bowheads photographed on 5 September 1986 near the **Kongakut** Delta had been photographed in 1985 (Table 42, Fig. 136). Both had been about 150 km to the east in Mackenzie Bay in 1985, one on 18 August and the other on 13 September.

Offshore Komakuk, 1985-86---Seven bowheads photographed offshore from **Komakuk** in 1985 (3) and 1986 (4) had been photographed in a previous year. These whales were 9.1-15.2 m long and included 3 **subadults** and 4 adults. Five **resightings** involved one year intervals; the others were at 4 and 5 yr intervals. Resightings were 8-65 d later in the year than the original sightings, averaging 32 d later ( $n = 7$ ). Net distances between sighting and refighting locations were 54-589 km, averaging 288 km. In general, the resightings were of two types: long distance **resightings** of large (**13.5+** m) whales, and shorter distance **resightings**, primarily of subs'dults.

The three long distance resightings (>500 km) offshore from **Komakuk** may reflect westward migrations that **some** large individuals undertake from summering areas in **Amundsen** Gulf and Franklin 'Bay. These three whales were first photographed in those areas in late July-early September of 1981, 1984 and 1985, and were re-photographed offshore from **Komakuk** during late September" of 1985 or 1986. These resightings were 21-65 d (mean 41 d) later in the year than the original sightings. The net distances between these sightings and resightings were 518-589 km, averaging 560 km. The one between-year refighting of a large whale close to shore off **Komakuk** (Table 42) was similar in many respects to these three **resightings** farther offshore. We do not know whether these adults had summered in the same area during the refighting year as in the first-sighting year. However, they were re-photographed late" in September 1985-86 during periods of active 'westward migration. As suggested in the '**Inter-Day Resightings**' subsection, above, use of waters offshore from **Komakuk** by migrants is probably of short duration.

The four other inter-year resightings offshore from **Komakuk** involved relatively short (<150 km) net distances from the location of the first photos : near **Komakuk** (2), Herschel Island (1), and King Point (1). These four resightings (3 **subadults** and one adult) occurred 8-39 d later in the year than the original sightings, averaging 25 d later. Net distances were 54-132 km, averaging only 84 km. Three of the four refighting **locations** were **west** of the first sighting locations. These four resightings were similar in most respects to the seven between-year resightings of **subadults** close to shore near **Komakuk**. Indeed, one whale originally photographed **near** King Point **in** 1984 was resighted offshore from **Komakuk** in 1985 and near **Komakuk** in 1986 (Table 42, footnote c).

West of MMS Study Area, 1986.--One large whale photographed west of the study area on 19 September 1986 (Koski and Johnson in prep.) had been photographed on 24 August 1982 near Herschel Island (Table 42, Fig. 136).

Summary.--The combined inter-day and inter-year refighting data confirm that the study area and environs are used both as a migration corridor and a feeding area. The area is used as a migration corridor by adult whales in late September. Many of these whales are traveling from summering areas far (>500 km) to the east, and their occupation of the study area appears to be brief. We have few data concerning their length of stay in the area, but a cow-calf pair photographed north of Komakuk on 27 September 1986 travelled west at a rate of 53 km/d over the subsequent 4 d period.

In contrast, some subadults use the area as a feeding area for more prolonged periods. The range of the numerous inter-day and inter-year resightings of primarily subadult whales encompasses the entire coastal area from the Kongakut Delta, AK, in the west to Shingle Point, Yukon, in the east, including part of Mackenzie Bay, waters near Herschel Island, and waters offshore from Komakuk. Some individuals, mostly subadults, reoccupy this area in subsequent years, and use it for prolonged periods within a year. For example, two of the inter-day resightings in the Komakuk area in 1986 involved bowheads that had been there in 1985 (Fig. 134). One of these whales was photographed offshore from Komakuk in 1985 and in nearshore Komakuk waters on three dates in 1986. The other was photographed near Komakuk on two dates in 1985 and two dates in 1986.

The entire nearshore area from Shingle Point to the Kongakut Delta may be, from the subadult bowhead's perspective, one elongated feeding area through which subadults may range freely. Within this area, nearly all of the large-scale inter-day and inter-year 'movements' were from east to west. This suggests that there may be a gradual movement west along the coast in the late summer period. However, the numerous between-day resightings of subadult bowheads very close to (or slightly east of) their earlier positions showed that many remain in one area for periods of at least several days. Also, the apparent scarcity of large-scale west to east movements could be partly the result of limited photographic coverage east of Herschel Island in September of 1985-86 (little after early Sept 1985; none in Sept 1986).

Subadults presumably migrate through the official study area after leaving the Komakuk-Yukon coast feeding area. However, we photographed active nearshore migrants on only one occasion (19 Sept 1985) during this study, and none of those whales were identified on any other date. The radio-telemetry data from 1986 showed that some bowheads from the nearshore Komakuk area moved west into the continental shelf portion of the official study area after leaving Komakuk.

#### Behavior of Bowheads in the Study Area

We observed the behavior of bowhead whales during 11 behavioral observation sessions on eight different days in September 1985, and during 17 sessions on 13 days in September 1986. These observations extended from the area off Kaktovik to Herschel Island (Fig. 111 on p. 267, Tables '43, 44). Total observation time was 15.2 h in 1985 and 17.3 h in 1986. In 1985, several

Table 43. Summary of behavioral observation sessions, 1985. For additional details, see Richardson et al. (1986b, p. 197).

Date 1985	Behav. Obs. Sess. #	Location <sup>a</sup>	Time of Obs.	Number of Whales		Feeding	Travelling	Active Socializing <sup>b</sup>	Predominant Orientation <sup>b</sup>	Predominant Speeds of Travel <sup>b</sup>
				in Circle	in General Area					
12 Sept	1	69°37'N 140°30'W	1628- 1817	5-8	10-15 in 15 km <sup>2</sup> /30-40 in 40 km <sup>2</sup>	near surface/ some in echelon/ Stom defecation		some—low level	random	slow & medium
13 Sept	2	69°37'N 140°07'W	1608- 1704	7-10	20-30 in 15 km <sup>2</sup>	near surface/ some defecation	possibly	some—low level	mainly west	slow & medium
19 Sept A	3	69°54'N 142°00'W	0930- 1219	1	3 in 20 km <sup>2</sup>	possible water column			mainly west	zero—slow
19 Sept B	4	69°40'N 141°00'W	1231- 1300	4 (400 m diam.)	8-10 <sup>c</sup> in 10 km <sup>2</sup>		strongly directed		nearly all west	medium
22 Sept <sup>1</sup>	5	70°14'N 139°56'W	1044- 1250	6-8	15-22 <sup>c</sup> in 20 km <sup>2</sup>	possible water column		up to 5 socializing	random	zero or slow
23 Sept A	6	69°37'N 140°38'W	1127- 1213	3-4	5-8 in 20 km <sup>2</sup> (110 calves)	possible water column	possible slow travel		mainly west	slow
23 Sept B	7	70°24'N 143°45'W	1640- 1815	4-6	4-6 in 4 km <sup>2</sup>	possible water column	possible slow travel		most west or north- west	slow
24 Sept	8	69°36'N 140°13'W	105a- 1143	4-6	15-25 in 40 km <sup>2</sup>	echelons; many open mouths; defecations		some	random	zero or slow
26 Sept A	9	69°52'N 139°58'W	1034- 1200	4	4-5 <sup>c</sup>	possible water column			Most west or north- west	slow
26 Sept B	10	70°29'N 143°23'W	154B- 1630	4-6	13-18 in 20 km <sup>2</sup>	possible water column		some	random	zero to medium
29 Sept	11	70°23'N 143°02'W	0926- 1034	5-6	12-15 <sup>c</sup> in 20 km <sup>2</sup>	possible water column; near surface	possibly	some	most west OR south- west	slow & medium

<sup>a</sup> See Figure 111A for locations.

<sup>b</sup> See Richardson et al. (1986b, p. 199) for details of socializing, Orientation and speed.

<sup>c</sup> Upper limit on number of whales in area is based on number of apparently different whales photographed here (Richardson et al. 1986b, p. 189).

of the behavioral sessions in offshore areas were in areas with loose pack ice, new ice, or both. The nearshore sessions in 1985 and both offshore and nearshore sessions in 1986 were in areas of open water. Water depths at observation locations ranged from about 8 to 280 m in 1985 (only one session in water >50 m deep), and about 5 to 48 m in 1986. Sea state was usually Beaufort 1 or 2.

General Activities. --In 1985, whales were encountered in aggregations covering from about 4 km<sup>2</sup> (in a small area surrounded by ice) to about 40 km<sup>2</sup>. The estimated mean number of whales in these areas was  $14 \pm \text{s.d. } 10$ , with a range of 3-40. Estimated number of whales within the circle of observation was  $5 \pm \text{s.d. } 2$  (range 1-10). In 1986, we sometimes observed small and localized groups of whales, as in 1985. However, on other occasions in 1986 we observed samples of the whales within larger and more widespread groups (e.g. on Sept 14, 15, 19, 20, 26A, 27).

Based on aerial observations of bowhead whales in the Canadian Beaufort Sea during summer, three main categories of feeding activity have been defined (Würsig et al. 1985a): near-surface feeding, near-bottom feeding, and water-column feeding. Near-surface feeding is readily recognized because the whales are visible as they move at the surface with mouths open and baleen exposed. Near-bottom feeding has not been observed directly, but has been recognized on the basis of whales surfacing with mud streaming from their bodies and, less commonly, their baleen. Consistence with this, stomachs of some bowheads (mainly small individuals) taken in Alaskan waters contain organisms that are normally found on or near the bottom (Lowry and Frost 1984; Lowry et al. 1987). Water-column feeding encompasses feeding at all depths other than the surface and the bottom. It undoubtedly includes some cases of feeding within a few meters of surface or bottom as well as feeding at mid-water. The fact that zooplankton is often concentrated in thin layers at mid-water depths (see 'Zooplankton' section, p. 187 ff, 219 ff) makes it likely that water column feeding is very common. However, water column feeding by bowheads has not been observed directly. It is assumed to occur when bowheads dive repeatedly in one area, but it is not possible to be sure that feeding has occurred during any specific dive (Würsig et al. 1985a).

Feeding near the surface or suspected feeding in the water column occurred on 19 of 21 days of observation and during 23 of 28 observation sessions (Tables 43, 44). Whales fed at or near the surface, with mouths open, during all or parts of nine sessions; on two of these occasions several whales travelled side by side in small echelons. Six of the nine cases of near-surface feeding were along the shore near Komakuk; others occurred in or just east of the official study area on 29 September 1985; and 5 and 26 September 1986. Water-column feeding was suspected to occur when whales dove for generally long times in an area. It may have occurred during at least seven sessions in 1985 and thirteen sessions in 1986 (Tables 43, 44). Nine of these cases were within the 'official' study area; three were slightly to the east, and eight were near shore off Komakuk. We saw defecations assumed to be indicative of recent feeding, during eight sessions; during six of these sessions at least some surface feeding was taking place, while only water column feeding was noted during the remaining two sessions. A mud plume, indicative of bottom feeding (Würsig et al. 1985a), was seen during only one

Table 44A. Summary of behavioral observation sessions, 1986.

Date 1986	Behav. Obs. Sess. #	Location <sup>a</sup>	Time & Length of Obs.	No. of Whales		Feeding	Travelling	Active Socializing <sup>b</sup>	Predominant Orientation <sup>b</sup>	Predominant Speeds of Travel <sup>b</sup>
				in Circle	in General Area					
3 Sept A	1	69°36'N 138°54'W	1213-1303		10-15	probable water column		no	mostly NE & E or S & SW	moderate
3 Sept B	2	69°33'N 139°28'W	1315-1326		6-10	long dives; possible water column		no	random	no data
5 Sept	3	69°49'N 141°48'W	1045-1206	10-13 +2 calf	20	defecation; mouths open; probable wet col & sfc; 1 bottom feeding		no	random	slow & moderate
7 Sept	4	69°49'N 141°37'W	1132-1244	6	12	possible water column; synchronized surfacings		no	random	slow & moderate
8 Sept	5	69°47'N 141°24'W	1438-1607	6-8	8	water column		no	random	slow & moderate
9 Sept	6	69°37'N 140°20'W	1609-1643	6-8	6-8	probable water column; synchronized dives; 1 defecation		some	mostly SW, W & W	slow & moderate
10 Sept	7	69°44'N 141°21'W	1022-1116	8-10	10-15	defecation; underwater blows; probable water column		some	random	slow & moderate
14 Sept	8	69°40'N 140°21'W	1025-1146		40-50	probable wet col & sfc; defecation; open mouths		some	random	slow & moderate
15 Sept	9	69°43'N 140°37'W	1001-1146	6-8	40-50	probable water column		low-level	random	slow
16 Sept	10	69°36'N 140°33'W	1126-1211	5-8	5-8	probable surface & water column		no	random	slow & moderate
19 Sept	11	69°37'N 139°33'W	1122-1236	6-8	50	sfc & probable wet col; defecation; open mouths		some	random	slow & moderate
22 Sept A	12	70°02'N 142°20'W	1633-1708	1	2	[Log Play]		no	W & SW (n = 2)	slow (n = 2)
22 Sept B	13	69°33'N 141°24'W	1721-1812	2	2		Yes	m	W	slow & moderate
26 Sept A	14	70°03'N 140°30'W	1142-1253	6-8	20-30	sfc and probable wet col; [Log Play]		some	mostly SW-W	slow & moderate
26 Sept B	15	70°09'N 141°32'W	1539-1621	1	1	[Log Play]		no	none recorded	zero (log play)
26 Sept C	16	70°10'N 141°26'W	1630-1735	5-6	5-6	possible wet-col by 2 mothers; [Log Play]		no	random	zero & slow
27 Sept	17	70°02'N 140°27'W	1241-1337	3-6	20+		Possible	some	mostly W-W	zero & moderate

<sup>a</sup> See Figure 111B for locations.<sup>b</sup> See Table 45 for details of socializing, orientation and speed.

Continued...

Table 44B (Concluded).

Date 1986	Behav. Obs. Sess. #	Dives		Size Classes <sup>b</sup>	Disturbance <sup>c</sup>	Calls	Depth (Approx.)	Sea State	Ice
		Duration	Distance <sup>a</sup>						
3 Sept A	1	0.1-0.8 min (n = 6)	unknown	no photos	none	yes	8 m	2	0%
3 Sept B	2	none timed	unknown	small subadults	none	unknown (no s'buoy)	10 m	2	0%
5 Sept	3	11-12 min (n = 2)	40-350 m (n = 5)	mostly subad; 2 calves seen	none	unknown (no s'buoy)	11 m	1	0%
7 Sept	4	synchronous; none timed	unknown	mostly subadults	faint seismic; assumed undisturbed	none heard (poor signal)	20 m	1	0%
8 Sept	5	1 measured -- 9 min	275 m (n = 1)	no photos	faint seismic; assumed undisturbed	none heard (poor signal)	19 m	3	0%
9 Sept	6	none timed	unknown	no photos	none	unknown (m s'buoy)	13 m	1+	0%
10 Sept	7	0.1-7 min (n = 9)	unknown	no photos	seismic confirmed	none heard	15 m	1	0%
14 Sept	8	2-17 min (n = 3)	350 m (n = 1)	mostly subad; 1 calf	none	yes, many	20 m	1	0%
15 Sept	9	6.3 min for calf (n = 1); no others timed	0-400 m (n = 5)	mostly subad; 1 calf	zodiac after 11:30	yes, many	27 m	1	0%
16 Sept	10	0.3-26 min (n = 5)	550 m (n = 1)	no photos	none	yes	5 m	1-3	0%
19 Sept	11	none timed	unknown	mostly subad; 2 calves	none	yes, many	9 m	1	0%
22 Sept A	12	0.3-0.6 min (n = 2)	0 m (n = 2)	no photos	none	none heard (poor signal)	22 m	2	0%
22 Sept B	13	0.5-17 min (n = 2)	unknown	no photos	none	yes	32 m	1	0%
26 Sept A	14	1m?awred- 0.2 min	<300 m (n = 2)	adults; large subadult; 4 calves in area	seismic assumed & confirmed until 12:47	yes, many	44 m	1	0%
26 Sept B	15	none timed	unknown	no photos	possible seismic	unknown (m s'buoy)	43 m	1	0%
26 Sept C	16	Calf: 3-12 min (n = 2) Other: 17-20 min (n = 3)	<100-500 m (n = 4)	adults & 2 calves	seismic confirmed after 17:24	yes, many	48 m	1	0%
27 Sept	17	none timed	unknown	adults; large subadults; 5 calves in area	none	unknown (no s'buoy)	45 m	2	0%

<sup>a</sup> Approximate distance travelled underwater during dives. Synchronous dives by cow and calf are counted as a single dive. Details in Table 52.

<sup>b</sup> Size class information is based on photogrammetric data (Fig. 131) supplemented by visual observations.

<sup>c</sup> See Table 46 for details of potential disturbance.

surfacing of a whale, on 5 September 1986, close to shore off the **Kongakut Delta (69°50'N, 141°45'W)**.

Vertical photographs of whales were acquired immediately after several of the behavioral observation sessions. From many of these photos, **it** was possible to determine whether the **whale's** mouth was open or closed **as** the aircraft passed over. Photos often showed open mouths on "occasions when behavioral observations provided no evidence **of** feeding near the surface (see Richardson et al. **1986b**, p. 195). It is possible that some 'water column feeding' occurs at depths shallow enough for the whale to be visible (and photographable) when directly **below** the aircraft, but too deep to be visible at the oblique angles from which most behavioral observations are obtained. Another possibility is that some whales that were **primarily** water column feeding or traveling were doing some **near-surface feeding** not detected by the behavioral observations.

Whales were definitely traveling toward the west during only two observation sessions, on 19 September 1985 near Demarcation Point (**141°W**), and on 22 September 1986 north of Demarcation Bay at **69°53'N, 141°24'W**. Except for two sessions involving log playing **whales** (22A and 26B Sept 1986), and a third session of possible travel (27 Sept 1986, see below), these were the only observation sessions for which we had no evidence of feeding, **and** it is likely that the whales were actively migrating. **During** five additional sessions, there was slow-to-medium speed travel generally westward, perhaps indicative of a low level of **migratory activity**. These cases were on 13, 23 (2 sessions) and 29 September 1985, and on 27 September 1986. We observed surface feeding **by** the traveling whales on: 13 September **1985**, and suspected **it** from open mouths seen just after the behavioral session on 27 September 1986. We suspected that water-column feeding was occurring during the other three sessions of possible westward movement. Thus, it is apparent that bowheads sometimes feed as they travel slowly west through the study **area**.

We observed **active social** interactions, generally of low intensity, during 14 of **28** observation sessions (Tables 43, **44**, 45). On 22 September 1985, social activity occurred frequently. On 12 occasions, socializing occurred when surface feeding or, possible water-column feeding was also occurring in the same general **area**; **on one** occasion (22B Sept 1986), socializing occurred **while** whales in the area were generally traveling **west**.

In 1985, calves were seen during four sessions, all well offshore. Two of these sessions were in the **'official'** study area (26, 29 Sept) and two were just to the east (22, 26 Sept; Fig. 129A on p. 310). On three **occasions**, two or more calves **were present** in the general area of observation. At times during periods of suspected water-column feeding, we saw lone calves at the surface, presumably waiting there **while** their mothers fed below (**cf.** Würsig et al. 1985a). On each of these four occasions, **subadult** whales were **also** noted (Fig. 130). In 1986., **we saw** calves during or just after seven sessions; **during** at least 5 of **these** 7 sessions, more than **one** calf was present (Table 44B, Fig. 129B). On 26C September, a calf played with a **small** log for at least 7 min **while** its presumed mother was diving.



Table 45. Socializing, headings and speeds during each behavioral observation session, September 1986. The values in the table are numbers of surfacings. Calves are excluded. See Richardson et al. (1986b, p. 199) for corresponding data from 1985.

	Date in September 1986																	Total
	3A	3B	5	7	8	9	10	14	15	16	19	22A	22B	26A	26B	26C	27	
socializing																		
None	25	2	33	24	12	5	44	39	27	34	44	6	4	11	1	7	12	330
Actively interacting	0	0	0	0	0	2	8	9	6	0	2	0	1	11	0	0	4	43
Proximity only <sup>a</sup>	0	0	0	2	0	0	3	12	0	0	0	0	5	4	0	0	0	26
Total	25	2	33	26	12	7	55	60	33	34	46	6	10	26	1	7	16	399
Heading (True)																		
N	1	1	5	1	0	0	3	5	6	3	4	0	0	0	0	0	0	29
NE	3	1	3	5	1	0	6	8	7	2	8	0	0	0	0	1	1	46
E	4	0	5	1	2	0	2	10	2	9	9	0	0	1	0	1	0	46
SE	0	0	4	4	1	1	3	0	2	2	7	0	0	0	0	2	1	27
S	8	1	0	3	2	0	8	7	1	1	1	0	0	2	0	1	0	35
Sw	2	1	6	5	4	2	8	3	4	3	4	1	0	3	0	0	1	47
W	0	2	4	1	2	2	14	12	6	7	6	1	10	2	0	0	8	77
NW	1	0	1	1	0	2	6	6	5	3	7	0	0	9	0	2	4	47
NNE-SSE	7	1	12	10	4	1	11	18	11	13	24	0	0	1	0	4	2	119
SSW-NNW	3	3	11	7	6	6	28	21	15	13	17	2	10	14	0	2	13	171
Total	19	6	28	21	12	7	50	51	33	30	46	2	10	17	0	7	15	354
Speed (Estimated)																		
Zero	1	0	3	1	1	1	1	2	4	2	6	0	0	0	0	1	2	25
Slow	2	0	7	7	2	3	13	15	10	4	12	2	4	11	0	2	0	94
Moderate	8	0	9	9	6	2	19	10	2	11	10	0	2	6	0	0	5	99
Fast	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
Change	2	0	7	6	1	1	3	14	8	3	11	1	1	5	1	3	5	72
Total	14	0	26	23	10	7	36	41	24	20	39	3	7	23	1	6	12	292

<sup>a</sup> Whales within 1/2 body length but not overtly interacting. Mothers with calves and whales skim-feeding in echelon formation are not counted as socializing.

**Whales** were heard to vocalize during 16 of 18 observation sessions when **sonobuoys** were used and were **working** properly. During the afternoon of 26 September 1985, high-frequency calls were heard while a calf was alone at the surface with the mother presumably feeding in the water column. We suspect that these unusual **calls** may have come from the **calf**, but this is not certain. A similar case was noted in August 1982 (Würsig et al. 1983, p. 86-87).

**Potential Disturbance\*.**--Several geophysical exploration vessels operated in or near the **official** study area during September 1985. The vessels present included some with high-energy noise sources for deep seismic exploration, and others with low-energy sources. Seismic exploration within the official study area was much reduced (and perhaps ended altogether) after pack ice was blown into the area in mid September 1985. However, some of the whales north of **Kaktovik** and near **Komakuk** in late September 1985 were still exposed to noise pulses from distant vessels operating outside the official study area. There was less seismic exploration in and near the study area in September 1986 than in September 1985, but some "whales were again exposed to noise pulses from distant seismic vessels.

Overall, seismic pulses were detected near **bowheads** during 12 of the 20 behavioral observation sessions when underwater sounds were monitored near whales--during 7 of 9 sessions in 1985 (Richardson et al. 1986b, p. 200) and 5 of 11 sessions in 1986 (Table 46). In most cases the pulses were weak. The strongest pulses received near whales were recorded on 22 September 1985 in deep water far north of **Komakuk**. The received level on that occasion, 123 dB re 1  $\mu$ Pa, was typical of levels 25 km or more from seismic vessels (Greene 1985). The strongest pulses recorded near whales in 1986 were 117-119 dB re 1  $\mu$ Pa, detected in shallow water off **Demarcation Bay** on 10 September. In no case during this study was the seismic vessel close enough to the whales to be noticed from the observation aircraft. Previous studies have shown that **bowheads** continue their 'usual activities in the presence of seismic pulses with the intensities "recorded during this study (Richardson et al. 1986a). Possible relationships of seismic noise to surfacing, respiration and dive patterns during this study are discussed below.

The characteristics of the noise pulses received near bowheads were quite variable (see Table 46 for 1986 data and Richardson et al. 1986b, p. 200, for 1985 data):

1. Pulse interval: In 1986 and on some occasions in 1985, the pulses were 10-14 s apart, which is typical of high-energy sources. On other occasions in 1985 the pulses were as closely spaced as one every 1.4 s (Fig. 137G), typical of low-energy sources.
2. Pulse duration: Single pulses ranged in duration from about, 0.1 to 0.9 s (Fig. 137).
3. Predominant frequency: The predominant received frequency content ranged from 100-20.0 Hz to 500-1000 Hz on various occasions (Fig. 137). Components below 100 Hz were presumably attenuated strongly because of the relatively shallow water at most recording sites.

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\* Acoustical analyses were performed by Greeneridge Sciences Inc.

Table 46. Characteristics of seismic pulses received near whales during behavioral observation sessions in 1986. (See Richardson et al. 1986b, p. 200, for corresponding 1985 data.)

Observation Session	Location	Approx. Depth (m)	Pulse Interval (s)	Main Frequencies (Hz) <sup>a</sup>	Peak Pulse Level (cIB re 1 $\mu$ Pa) <sup>a</sup>	Ambient Level Between Pulses <sup>a,b</sup>
7 Sept	off Kongakut Delta	20	Irreg.	300	115e	103
8 Sept	off Kongakut Delta	19	Irreg.	420	107-110 <sup>e</sup>	103
10 Sept	off Demarcation Bay	15	10.5	250-300	117-119	91-95
26 Sept A	far off Komakuk	44	10.5 <sup>c</sup>	150-350	110-118	92
26 Sept C	far off Kongakut Delta	48	10 <sup>d</sup>	150-350	113-116	91-93

<sup>a</sup> Noise analyses were performed by Greeneridge Sciences, Inc., following methods of Greene (1985).

<sup>b</sup> 20-1000 Hz band, averaged over 30 s excluding times of arrival of seismic pulses, in dB re 1  $\mu$ Pa.

<sup>c</sup> Seismic pulses ended at 12:47, during behavioral observations.

<sup>d</sup> Seismic pulses started at 17:24, during behavioral observations.

<sup>e</sup> Most pulses on 7 and 8 Sept were weaker than this, and barely audible.

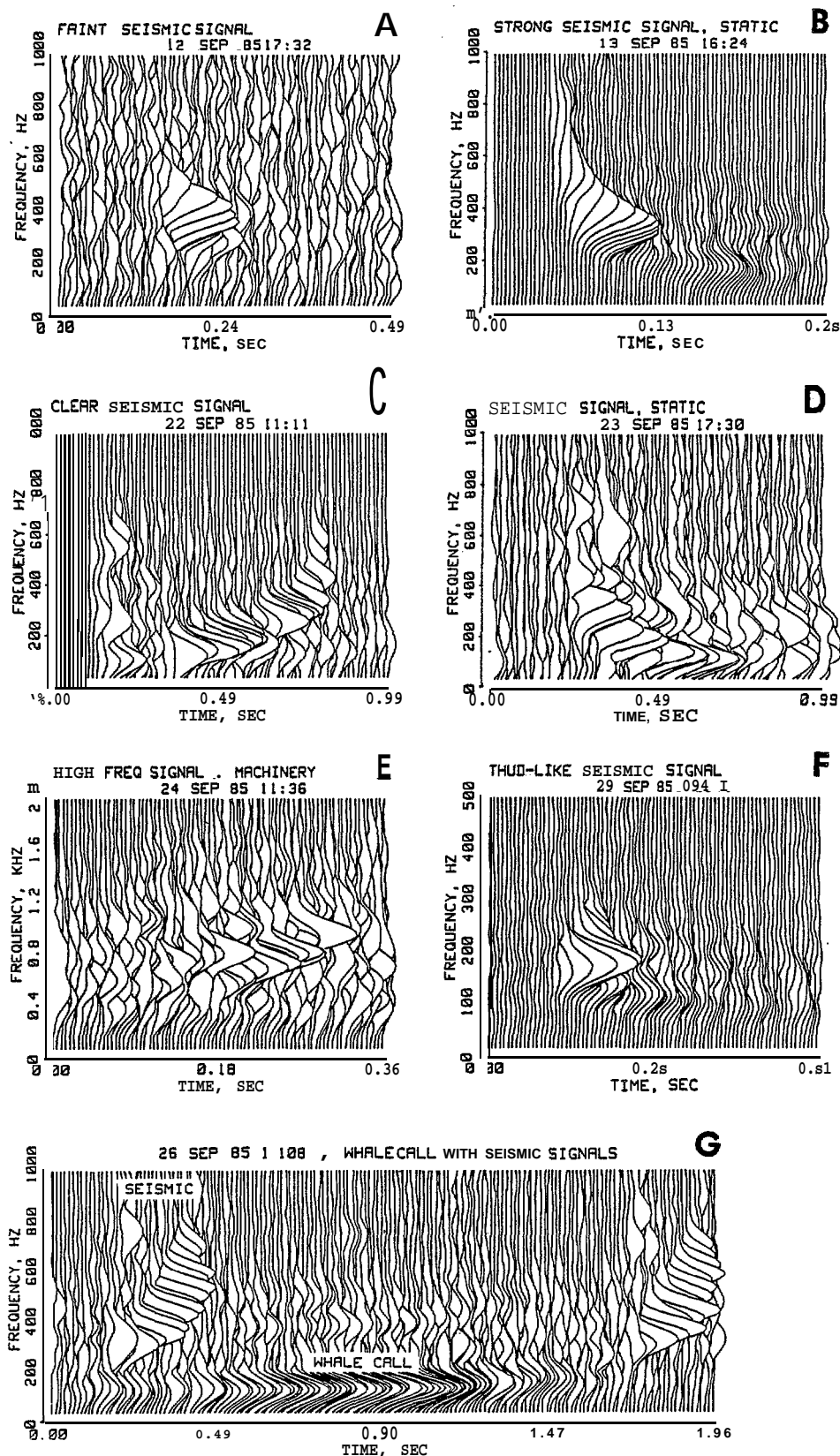


FIGURE 137. Frequency vs. time characteristics of underwater noise pulses received by sonobuoys at locations where bowhead whales were observed, September 1985. Waterfall analyses were done by Greeneridge Sciences Inc. Note that both scales vary among panels A-G.

4. Temporal pattern of frequencies: The predominant frequency **sometimes** swept downward during the brief interval **while** a **single pulse** was being received (**Fig. 137A,B,D**). This **downswept** frequency pattern is typical for seismic pulses received **in** shallow waters **of the Beaufort Sea** (Greene 1985). However, on some occasions during 1985 there was **an** upswept frequency pattern (**Fig. 137E,G**), or a more complex pattern **that** included an upsweep as one component (**Fig. 137C**).

Within any one observation session these four pulse characteristics remained more or **less constant**, as one would expect **during** continuous operation of a **single** noise source.

**During** 3 of 28 behavioral observation sessions, other sources of potential noise disturbance were evident. On one occasion (24 Sept 1985), **whales** near **Komakuk** DEW site were exposed not **only** to faint seismic **pulses** but **also** to faint engine noise, possibly from generators at **Komakuk**. On another **occasion** (19 Sept 1985), whales were probably exposed to noise from a distant maneuvering boat ('**Annika Marie**') and zodiac during a radio tagging attempt. **In** neither of these cases was the behavior of the whales believed to be seriously affected by the noise. On 15 September 1986, a zodiac with a special **type** of outboard motor approached the **whales** at the end of the behavioral observation session. Its engine was modified to reduce underwater noise (**B. Mate, pers. comm.**), but nonetheless strong underwater noise was received at **medium** and high frequencies including a harmonic family of strong tones at **1522, 3042 and 4564 Hz**.

Behavioral observations under potentially disturbed conditions are distinguished from those under presumably undisturbed conditions in most of the following analyses.

Surfacing, Respiration and Diving Behavior.--In order **to estimate the amount of feeding within the study area**, it is necessary to estimate average distance **travelled** during feeding dives, duration of feeding dives, and interval between successive dives. From these **data**, it may **be possible to make rough** estimates of the number of dives per day and volume of water **filtered per day**. Data on respiration are important **in** estimating energy utilization. **It is also** necessary to determine **whether** these behavioral characteristics vary according to location **or** depth, status or activity of the whale, presence of potential sources of disturbances and other factors.

We routinely recorded four measures of surfacing, respiration and diving behavior, using **the** same definitions and criteria as in our previous studies (**Würsig et al. 1984**):

- **blow intervals**--the intervals between successive breaths within surfacings (n = 2031);
- number of **blows** per surfacing (n = 123);
- duration of surfacing (n = 192); and
- duration of dive (n = 60).

These **sample** sizes exclude calves. The means, ranges, and distributions of these four variables during September 1985 and 1986 (**Fig. 138, 139**) were generally similar **to** those observed during previous studies in the **Beaufort**

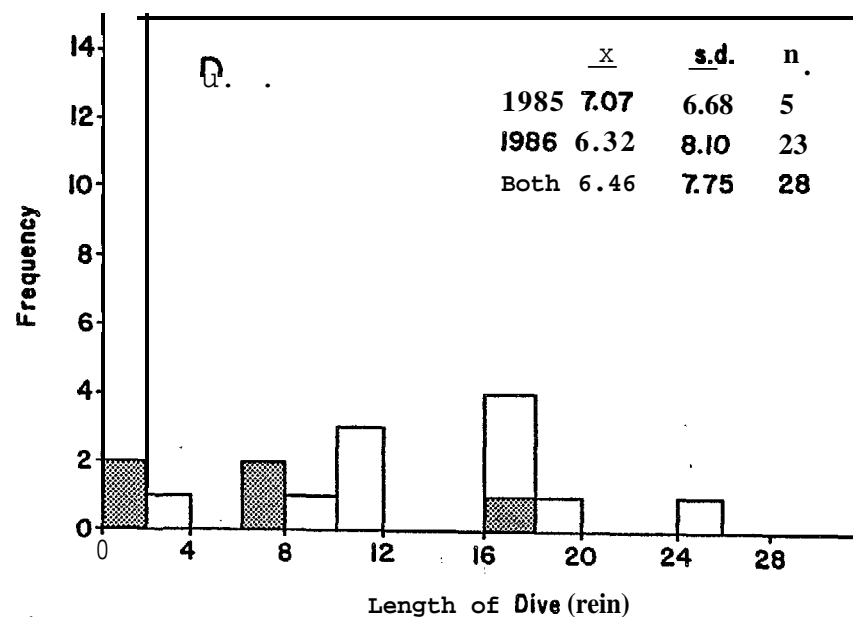
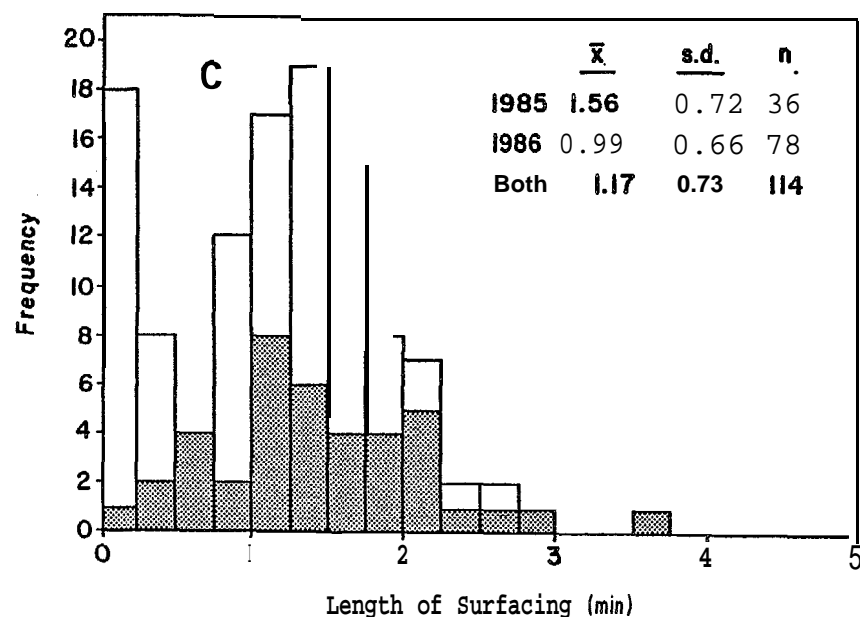
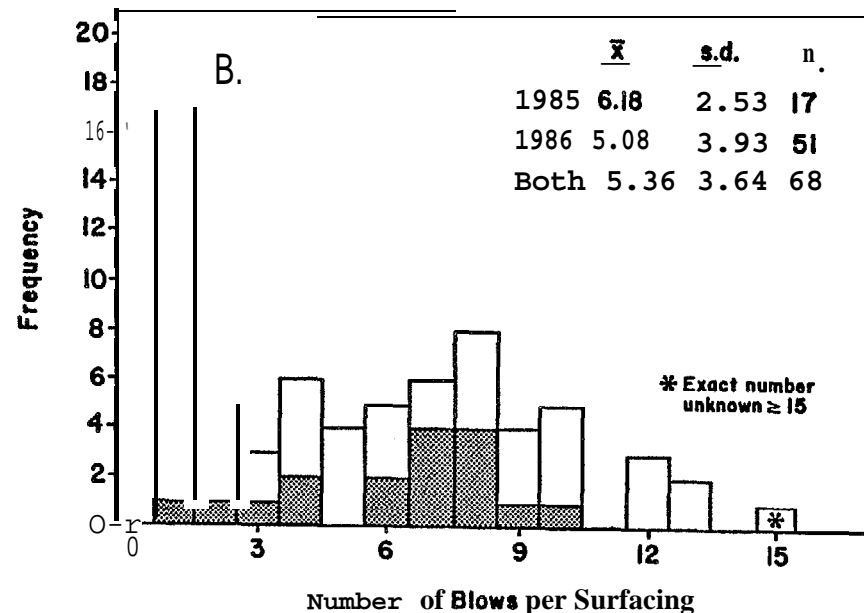
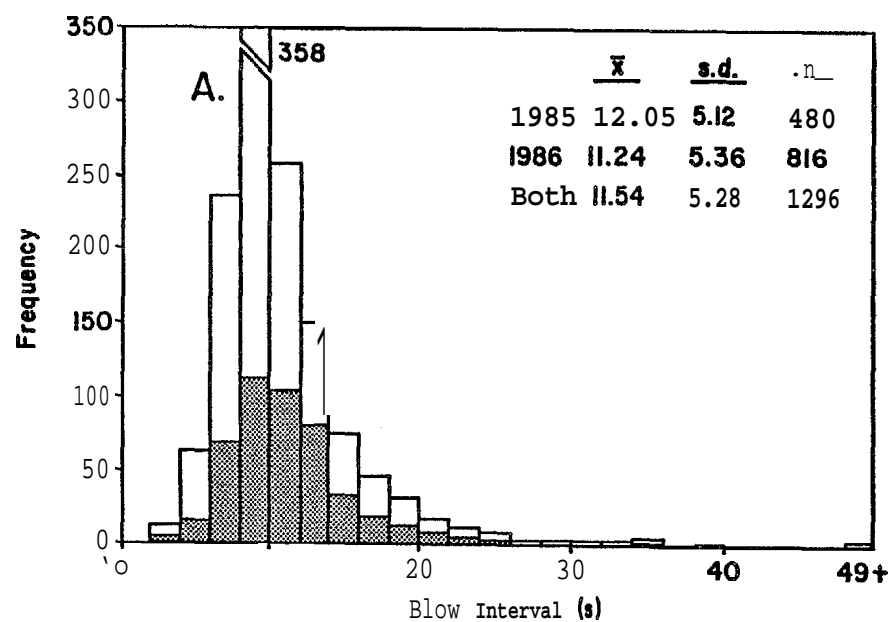


FIGURE 138. Frequency distributions of the principal surfacing, respiration and dive variables recorded under presumably undisturbed conditions, September 1985 (shaded) and 1986 (open).

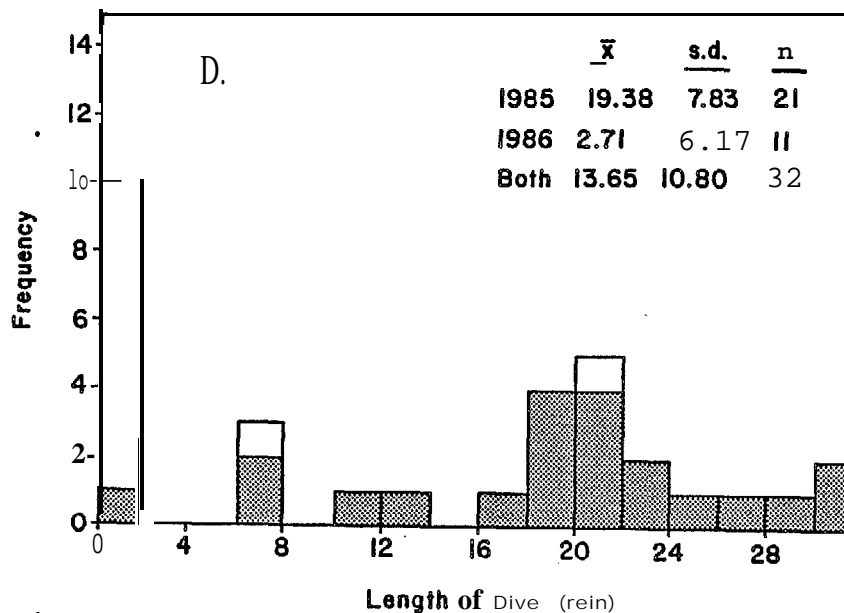
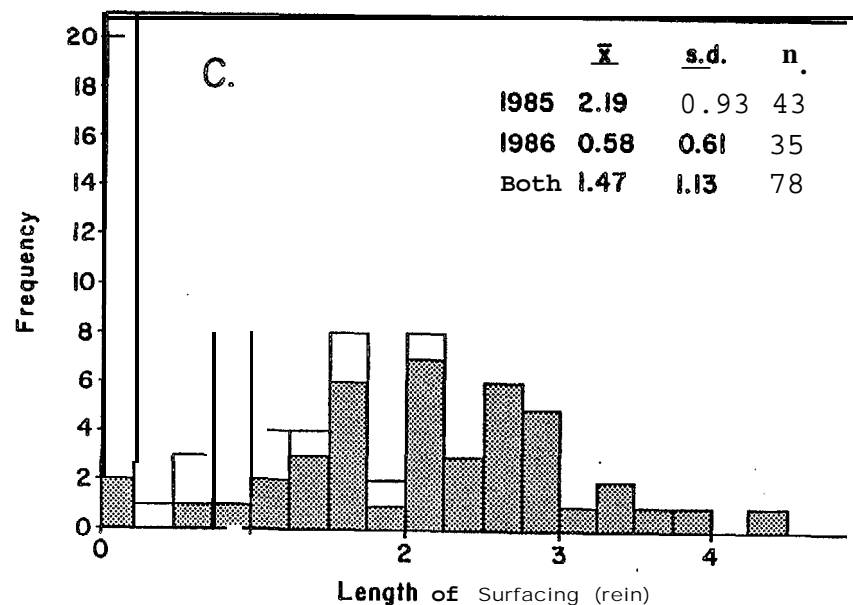
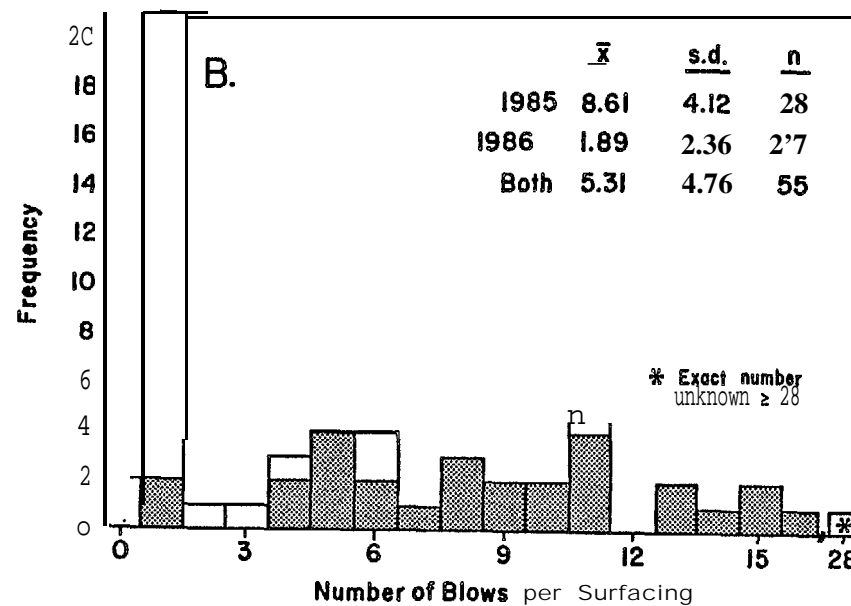
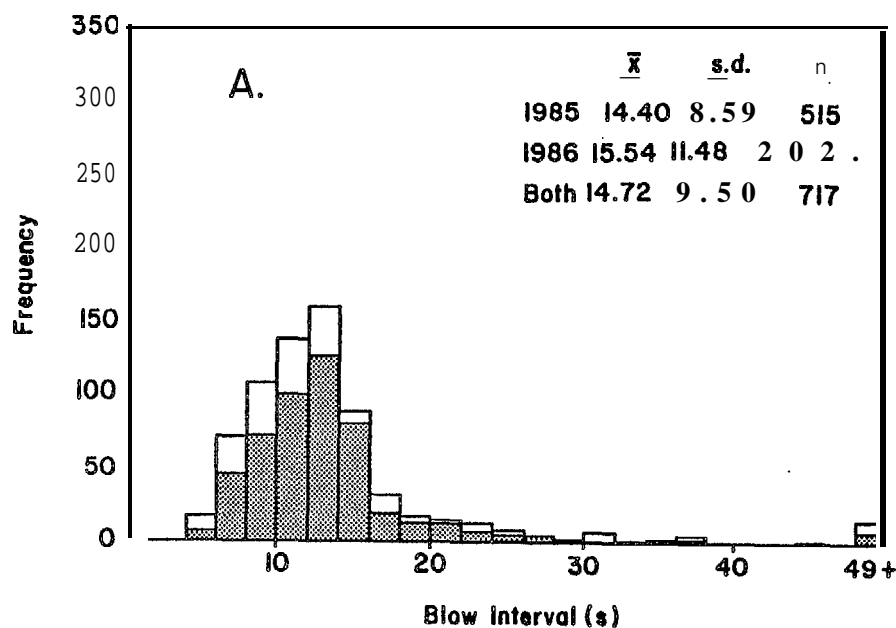


FIGURE 139. Frequency distributions of the principal surfacing, respiration and dive variables recorded under potentially disturbed conditions, September 1985 (shaded) and 1986 (open).

Sea during summer (Würsig et al. 1984, 1985b) and autumn (Ljungblad et al. 1984b, 1985b; Fraker et al. 1985).

Intercorrelations: The durations of the dives preceding and following a surfacing were correlated more strongly during September '1985-86 than during summer 1980-84 ( $r_s = 0.862$  vs. approx.  $0.435$ ; Table 47A). Previous autumn results are inconsistent on this point: the correlation between previous and subsequent dive duration was weak in autumn 1983 ( $r_s = 0.286$ ,  $n = 32$ , ns; undisturbed whales only--Ljungblad et al. 1984b) but strong in autumn 1984 (product-moment  $r = 0.782$ ,  $n = 38$ ,  $p < 0.001$ ; based on potentially disturbed whales--Ljungblad et al. 1985b). In general, during both summer and autumn it is likely that consecutive dives tend to be of similar durations, since bowheads tend to engage in one activity for at least a few hours or perhaps a few days. "

In September 1985-86, as during other studies in summer and autumn, number of blows during a surfacing was positively correlated with the duration of the surfacing (Table 47B).

Previous summer work has shown that both number of blows per surfacing and duration of surfacing are positively correlated with duration of the preceding dive (Table 47C,D). During summer, correlations of both blows/surfacing and surface time with duration of the following dive were less strong although still significant (Table 47E-F). During September 1985-86, all of these correlation coefficients were higher than in the earlier summer work. In general, during both summer and autumn bowheads tend to remain at the surface for longer and breathe more times per surfacing when dives are long than when dives are short.

Disturbance Effects: Previous studies have shown that the four surfacing, respiration and dive variables can be affected by seismic or boat noise (Ljungblad et al. 1985b; Richardson et al. 1985b,c, 1986a). During 7 of 28 behavioral observation sessions, whales were classified as "potentially disturbed by underwater noise from seismic exploration (Sept 13, 22, 23B, 26A in 1985; and Sept 10, 26A, 26C in 1986). On a few other occasions with fainter seismic noise, we treated the data as presumably undisturbed. During two sessions, whales were observed during possible boat disturbance (Sept '19A in 1985; part of Sept 15 in 1986), but this disturbance represented only a small portion of our data base, and is not summarized here.

The mean blow interval was significantly longer with seismic noise than under presumably undisturbed conditions and the mean duration of surfacing was marginally so (Table 48A). In and near the official study area, only mean blow interval was higher under seismic than under presumably undisturbed conditions (Table 48B; Fig. 140). Along the Yukon coast near Komakuk, blow interval and duration of surfacing were both significantly higher with seismic noise. No such differences were found for number of blows per surfacing or duration of dive, but sample sizes were low for some comparisons (Table 48A-C; Fig. 140).

Previous summer and autumn data from the Beaufort Sea indicated that durations of surfacings and dives tended to be reduced when seismic vessels or boats were nearby. For duration of surfacing the opposite trend was observed here, at least in the Komakuk area. However, all 'seismic' data for the



Table 47. Intercorrelations between standard surfacing, respiration and dive variables in autumn 1985-86 (this study), autumn 1983 (Ljungblad et al. 1984b), and summer 1980-84 (Würsig et al. 1985b)<sup>a</sup>.  $r_s$  is the Spearman rank correlation. Calves are excluded. For 1985-86, data for 'presumably undisturbed' and 'potentially disturbed' whales are presented separately and pooled.

A. Previous dive vs. subsequent dive					B. Number of blows vs. surface time				
1985-86 Undist.	$r_s = 1.000$	n = 8	***		1985-86 Undist.	$r_s = 0.896$	n = 68	***	
Dist.	0.730	17	***		Dist.	0.843	55	***	
All	0.862	25	***		All	0.876	123	***	
1983 Undist.	0.286	32	ns		1983 Undist.	0.475	163	***	
Summer Undist.	~ 0.435	163	***		Summer Undist.	-0.849	607	***	
C. Previous dive vs. surface time					D. Previous dive vs. number of blows				
1985-86 Undist.	$r_s = 0.695$	n = 21	**		1985-86 Undist.	$r_s = 0.649$	n = 16	*	
Dist.	0.801	27	***		Dist.	0.727	20	*	
All	0.794	48	***		Au	0.717	36	***	
Summer Undist.	~ 0.355	265	***		Summer Undist.	~ 0.455	237	***	
E. Subsequent dive vs. surface time					F. Subsequent dive vs. number of blows				
1985-86 Undist.	$r_s = 0.644$	n = 10	(*)		1985-86 Undist.	$r_s = 0.436$	n = 8	ns	
Dist.	0.841	21	***		Inst.	0.822	15	**	
All	0.784	31	***		Au.	0.709	23	**	
Summer Undist.	~ 0.194	235	**		Summer Undist.	~ 0.258	216	***	

<sup>a</sup> Summer  $r_s$  values are weighted averages of the five annual correlation coefficients reported by Würsig et al. (1985b), with approximate significance levels.

ns  $p > 0.1$

\*\*  $0.01 > p > 0.001$

(\*)  $0.1 > p > 0.05$

\*\*\*  $p \leq 0.001$

\*  $0.05 \geq p > 0.01$

Table 48. Summary statistics for the principal surfacing, respiration and dive variables, September 1985-86. Calves are excluded except where noted in section E. 'Official Study Area' lines include observations in offshore waters north of Komakuk on 22 and 26 Sept 1985 and on 26 and 27 Sept 1986.

	Number of Obs. Sessions	Blow Interval (s)				Number of Blows per Surfacing				Duration of surfacing (min)				Duration of Dive (min)			
		Mean	s.d.	n	Test <sup>a</sup>	Mean	s.d.	n	Test	Mean	s.d.	n	Test	Mean	ad.	n	Test
<b>A. All Areas</b>																	
Undisturbed	20	11.55	5.28	1295	t'	5.36	3.64	69	t	1.17	0.73	114	t	6.46	7.75	28	u, ns
Seismic	7	14.81	9.81	670	***	5.02	4.73	52	ns	1.41	1.16	92	(*)	11.64	11.39	25	(z = 1.30)
<b>B. Official Study Area</b>																	
Undisturbed	10	12.72	5.64	574	t'	6.27	2.98	22	t'	1.57	0.73	32	t	9.44	7.29	12	u, ns
Seismic	6	14.73	9.87	609	***	5.08	4.89	48	ns	1.037	1.20	63	us	11.98	11.83	23	(z = 0.10)
<b>C. Komakuk Area</b>																	
Undisturbed	10	10.61	4.79	721	t'	4.91	3.88	46	t	1.02	0.66	82	t	4.22	7.54	16	b
Seismic	1	15.66	9.18	61	***	4*25	2.50	4	ns	1.69	0.84	9	**	7.72	0.19	2	
<b>D. Off. Study Area vs. Komakuk</b>																	
Undisturbed	10/10	see above			t ***	see above			t ns	see above			t ***	see above			u = 45 *
Seismic	6/1	see above			t ns	see above			e' ns	See above			t ns	see above			b
<b>E. All Obs. Sessions with Calves</b>																	
Undisturbed																	
Calves	6	15.62	10.49	111	t'	5.67	4.16	3		1.92	1.31	4	t'	10.78	6.23	3	
others with calves	6	12.79	5.80	515	**	6.78	2.73	18	b	1.68	0.65	29	ns	12.29	6.15	7	b
seismic																	
Calves	4	13.28	9.48	71	t	6.00	2.65	3		2.16	1.42	6	t	13.58	2.40	4	u = 13.5
Others with calves	4	15.67	10.49	499	(*)	9.10	4.47	21	b	2*34	0.99	30	ns	19.00	9.90	14	ns

<sup>a</sup> ns means  $p > 0.1$ , (\*) means  $0.1 \geq p > 0.05$ , \* means  $0.05 \geq p > 0.01$ , \*\* means  $0.01 \geq p > 0.001$ , \*\*\* means  $p \leq 0.001$ .

<sup>b</sup> Sample size too small for test.

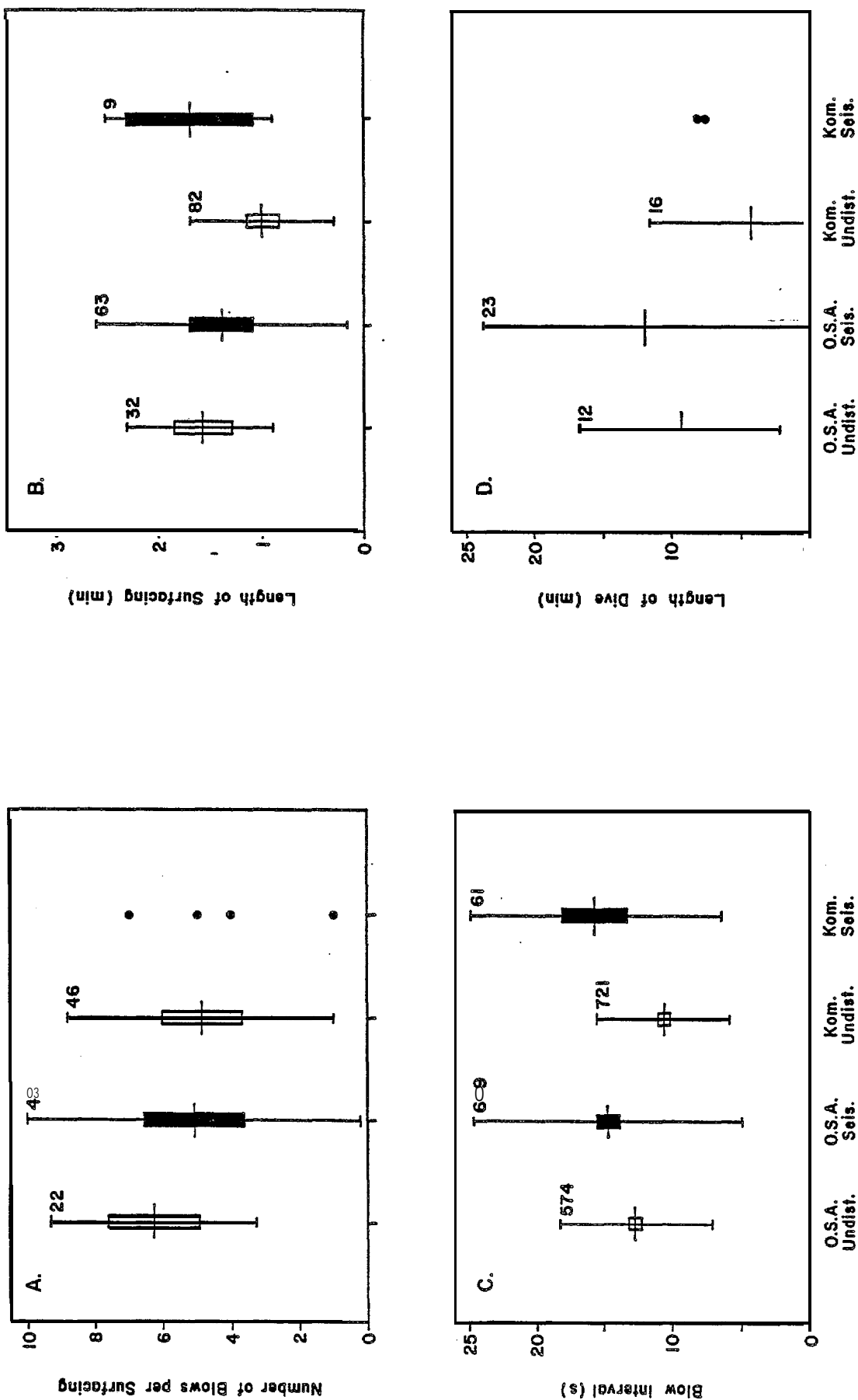


FIGURE 140. Comparison of the principal surfacing, respiration and dive variables recorded in and near the official study area vs. along shore near Komakuk under presumably undisturbed vs. potentially disturbed by seismic noise pulses' conditions. When  $n > 5$ , the mean  $\pm$  standard deviation are shown by thin horizontal and vertical lines. The 95% confidence interval is shown by a rectangle (omitted from D because of skewed dive duration<sub>95</sub>). When  $n < 5$ , the individual values are shown.

**Komakuk** area came from a **single** observation **session** (13 Sept 1985). During the observations in September 1985-86, the seismic vessels were many kilometers away, and the actual disturbance to the **whales** was probably **minimal**. We suspect that few of the bowheads studied in September 1985-86 were reacting overtly to seismic noise, **although** the 'Calves vs. Other **Bowheads**' data (see **below**) provide some evidence of an effect. Natural factors that differed between observation sessions may have been responsible for **the** apparent differences **in** behavior in the presence and absence of weak sources of potential disturbance. Nevertheless, we separate data during seismic and presumably undisturbed conditions in most subsequent analyses.

Whales in **Official Study Area vs. Komakuk** Area: Seventeen of the 28 observation sessions were in the official **study** area or just east of it in offshore waters; eleven sessions were east of **the** study area in shallow water **close** to the Yukon coast near **Komakuk** (Alaska/Yukon border east to Herschel Island; Fig. 111 on p. 267). We examined whether the behavior of bowheads in shallow water near Komakuk was similar to that elsewhere in and near the study **area**. For undisturbed whales, **all** four surfacing, respiration, and dive variables tended to be higher for whales in the official study **area** than for whales near Komakuk; the differences were significant for **blow** interval, duration of surfacing, and duration of dive (Table 48D; Fig. 140). The **lower** values for whales near **Komakuk** were probably related to the fact that these whales were in shallow water. **All** four variables tended to be lower for whales in shallow water (see Table 51, later).

For whales exposed to seismic noise, **no** significant differences were found between the two areas; however, **sample** sizes were **small** for **all** variables except for blow interval.

**Calves vs. Other Bowheads:** We gathered few behavioral data on calves during September 1985-86. The mean blow interval was longer for undisturbed calves than for other **bowheads** seen during the same observation sessions. However, in the presence of seismic noise, the mean **blow** interval was marginally shorter for calves than for "others (Table 48E). As in earlier studies (Ljungblad et al. 1985b; Richardson et al. 1985c, 1986a), the **mean** blow interval of 'non-calves' was **significantly higher in the presence of seismic noise** than in its absence (Table 48A). Hence", the data suggest that **blow** intervals of **calves** may be less affected by seismic noise than those of non **calves**, or possibly even show a reversed trend.

Sample sizes for other variables were too **low**, in the case of **calves**, for meaningful comparisons of calves **vs.** other whales. In the autumn of 1983, undisturbed calves exhibited relatively long surfacings with many **blows** (Ljungblad et al. 1984b). In previous summers, calves tended to have relatively long **blow** intervals and few **blows** per surfacing (Würsig et al. 1985b); the present data are consistent with those trends. In view of the generally **low** sample sizes in autumn and the indications of differences between **calves** and non calves, we have continued our previous practice of treating **calves** separately from other **whales** in analyses of surfacing, respiration and dive variables.

Effects of Whale Activity: We categorized 26 of the observation sessions into five groups based on- the main activities of the bowheads:

- apparent water-column feeding,
- apparent water-column feeding plus slow-moderate travel,
- apparent water-column feeding plus definite near-surface feeding,
- definite near-surface feeding, and
- travel.

We then compared respiration, surfacing, and dive variables for whales engaged in these five activities. Two sessions, those designated 22A and 26B September 1986, were not included in these analyses because they involved **whales** (one on each occasion) playing with a log at the surface. In this subsection, we consider only the 19 observation sessions when activities **could** be categorized and when the whales were presumably undisturbed.

**Blow** intervals were more often significantly different among whale activities than were other respiration, surfacing and dive variables probably because of the much greater sample sizes available for **blow** intervals than for the other variables (Table 49). For presumably undisturbed whales, blow intervals of whales feeding in the water column and of traveling whales were higher than those of whales engaged in water-column feeding plus traveling, water-column feeding plus surface feeding, and surface feeding **only** (Table 49A). The longer **blow** intervals during water-column feeding as compared to other activities are **due** almost exclusively to data from the **Komakuk** area (Table 49C). No such trend was observed in the official study area (Table 49B) .

The **only** other situation in which a surfacing, respiration or dive variable differed significantly according to whale activity was duration of surfacing of undisturbed whales in the **Komakuk** area. As expected (Würsig et al. 1986), whales showed longer surface times when engaged in surface feeding or in a combination of water-column and surface feeding than when engaged in water-column feeding only (Table 49C).

During previous summer work, we found that bowheads feeding at the surface tended to have long surface times and **long** blow intervals (Würsig et al. 1985b, 1986). Although whales feeding near the surface off **Komakuk** exhibited long surface times, **blow** intervals were not consistently longer during surface feeding than during other activities. One possibly confounding factor exists in the **data**: we categorized the predominant activity during a behavioral observation session, but some particular whales that we observed did **not** behave as categorized. For example, during sessions labelled 'surface feeding', not **all** the whales were feeding at the surface throughout the session. In contrast, in analyzing surface feeding in summer, we considered only the individual surfacings during which particular whales were observed feeding at the surface. Low sample sizes for some activities in autumn prevented us from categorizing whales in the same way as for summer data.

Effects of Speed of Motion: We categorized speed of **motion** of whales **while** at the surface **into** four **relative** speeds, from **none** to fast. The category 'none' signifies a whale that is not noticeably moving its **tail** and appears to make no forward progress. Fast movement generates a wave of water at the head of the whale, as well as whitewater along the sides and near the **tail**. The two intermediate categories of **slow** and mo-derate are less **clearly** separated, with slow movement indicating **barely** perceptible forward progress,

Table 49. Relationships between activities of undisturbed whales and the principal surfacing, respiration and dive variables, **September** 1985-86. Data from potentially disturbed **whales** and **all** calves are excluded. 'Official Study Area' includes observations in offshore waters north of **Komakuk** on 22 and 26 Sept **1985** and on 26 and 27 Sept 1986.

	Number of Obs. Sessions	Blow Interval (s)				Number of Blows per Surfacing				Duration of Surfacing (min)				Duration of Dive (min)			
		Mean	s.d.	n	Test <sup>a</sup>	Mean	s.d.	n	Test	Mean	s.d.	n	Test	Mean	s.d.	n	Test
A. All Areas																	
Water-col Feeding	8	12.83	6.18	350	ANOVA;	4.88	3.30	17	ANOVA;	1.25	0.84	32	ANOVA;	6.46	8.31	10	-
Water-col & Travel	1	10.06	2.53	18	F =	-	-	0 <sup>b</sup>	F =	-	-	0 <sup>b</sup>	F =	-	-	0 <sup>b</sup>	-
Water-col & Sfc Feed	5	10.51	4.77	611	13.80	5.49	4.00	35	0.36;	0.99	0.62	49	2.69;	7.47	8.22	12	-
Near Surface Feed	2	11.40	4.99	183	***	5.63	2.72	8	ns	1.45	0.64	23	(*)	4.09	4.07	2 <sup>b</sup>	-
Travel	3	12.72	3.55	123		6.67	4.08	6		1.41	0.79	8		8.76	11.70	2 <sup>b</sup>	-
B. Official Study Area																	
Water-col Feeding	4	12.65	5.73	257	ANOVA;	7.28	1.77	8	ANOVA;	1.80	0.67	16	ANOVA;	15.63	4.50	4 <sup>b</sup>	-
Water-col & Sfc Feed	2	12.37	6.24	184	F = 0.19;	5.83	2.48	6	F = 0.52;	1.59	0.61	6	F = 0.88;	8.10	4.59	4 <sup>b</sup>	-
Travel	3	12.72	3.55	123	ne	6.67	4.08	6	ns	1.41	0.79	8	ns	8.76	11.70	2 <sup>b</sup>	-
C. Komakuk Area																	
Water-col Feeding	4	13.32	7.30	93	ANOVA;	2.67	2.69	9	ANOVA;	0.71	0.61	16	ANOVA;	0.35	0.26	6	-
Water-col & Travel	1	10.06	2.53	18	F =	-	-	0 <sup>b</sup>	F =	-	-	0 <sup>b</sup>	F =	-	-	0 <sup>b</sup>	-
Water-col & Sfc Feed	3	9.71	3.70	427	17.85;	5.41	4.27	29	1.97;	0.90	0.58	43	8.81;	7.15	9.83	8	-
Near Surface Feed	2	11.40	4.99	183	***	5.63	2.72	8	ns	1.45	0.64	23	***	4.09	4.07	2 <sup>b</sup>	-

<sup>a</sup> ns means  $p > 0.1$ , (\*) means  $0.1 > p > 0.05$ , \* means  $0.05 \geq p > 0.01$ , \*\* means  $0.01 \geq p > 0.001$ , \*\*\* means  $p \leq 0.001$ .

<sup>b</sup> Sample size too small for statistical test.

and moderate movement indicating a definite forward motion with strong tailbeats but with no generation of whitewater. Because of the inability of aerial observers to measure speeds of motion accurately in units of distance per time, we present only the relative speeds here.

There was no discernible relationship between mean blow interval and speed of motion. However, number of blows per surfacing, duration of surfacing, and duration of dive all decreased from no speed to moderate speed. The few data available for fast speed followed the same trend (Table 50). This trend for shorter surfacings, shorter dives and fewer blows per surfacing with increasing speed was the same for presumably undisturbed whales, potentially disturbed whales, and all whales combined (Table 50).

observations in the autumn of 1984 demonstrated a similar trend, with mean number of blows per surfacing, duration of surfacing, and duration of dive all tending to decrease from no speed to fast speed (Ljungblad et al. 1985b). This trend existed for both presumably undisturbed whales and for whales subjected to seismic noise. As in the autumn data for 1985-86, blow interval showed no consistent relationship to speed. In contrast, data from five years, of observations (1980-84) in summer do not show clear relationships between speed and any of the respiration, surfacing, and dive variables (Dorsey et al. in prep.). We do not know why there should be such a difference between summer and autumn. It may be due, at least in part, to the greater importance of travel in autumn than in summer, even though travel often occurs at the same time as other activities (primarily feeding) in both summer and autumn. Directed and prolonged travel at moderate or fast speed may have a more profound effect on respiration, surfacing and dive variables than do other behaviors.

Effects of Water Depth: Depths of water at locations where whales were observed systematically during September 1985-86 almost always were 5-50 m. The one exception involved whales in water 280 m deep on 22 September 1985, when there was moderately strong seismic noise. Our overall results from September 1985-86 showed that mean blow interval, number of blows per surfacing, duration of surfacing, and duration of dive were all positively correlated with water depth (Table 51). The same trends were evident for presumably undisturbed whales, potentially disturbed whales, and all whales.

Previous observations in both summer and autumn have also demonstrated that mean duration of surfacing and mean number of blows per surfacing tend to increase with increasing water depth (Ljungblad et al. 1984b, 1985b; Würsig et al. 1985b). Previous summer data, and autumn data for presumably undisturbed whales (Ljungblad et al. 1985b), indicate that mean duration of dives increases with increasing water depth. No clear correlation between blow intervals and water depth has been demonstrated in previous work.

**Distances Travelled Underwater:** To estimate the volume of water filtered by a bowhead whale during a feeding dive, an estimate of the distance travelled during an average dive is needed. When possible, we estimated the distance between the locations where a recognizable whale dove and resurfaced. The estimates were done by eye from the circling aircraft, and were based on estimates of bearings and distances from dye markers and distinctive ice pans.

Table 50. Relationship between speed of motion and the various surfacing, respiration and dive variables, September 1985-86. Calves are excluded.

speed	Presumably undisturbed				Potentially Disturbed				All whales			
	Mean	s.d.	n	Test <sup>a</sup>	Mean	s.d.	n	Test	Mean	s.d.	n	Test
<b>Blow Interval (s)</b>												
None	12.12	6.68	165	F =	14.39	11.10	74	F =	12.82	8.35	239	F =
Slow	11.47	5.34	363	1.73	15.12	10.15	254	0.20	12.97	7.89	617	2.91
Moderate	11.04	4.21	252	ns	14.41	7.86	37	ns	11.47	4.94	289	*
Fast	13.38	3.50	8				0 <sup>b</sup>		13.38	3.50	8	
<b>No. Blows/Surfacing</b>												
None	9.25	2.87	4	H =	9.67	4.63	6	H =	9.50	3.84	10	H =
slow	8.00	2.42	13	10.00	7.23	4.17	13	14.95	7.62	3.36	26	24.98
Moderate	3.91	2.91	11	**	1.25	0.62	12	***	2.52	2.43	23	***
Fast	1.00		1 <sup>b</sup>		1.00		1 <sup>b</sup>		1.00	0.00	2 <sup>b</sup>	
<b>Duration of Surfacing (min)</b>												
None	1.74	0.75	10	H =	2.36	0.85	8	H =	2.02	0.83	18	H =
slow	1.43	0.52	23	13.02	1.66	0.78	18	22.87	1.53	0.65	41	34.88
Moderate	0.89	0.54	18	**	0.27	0.56	13	***	0.63	0.62	31	***
Fast	0.07		1 <sup>b</sup>		0.18		1 <sup>b</sup>		0.13	0.08	2 <sup>b</sup>	
<b>Duration of Dive (min)</b>												
None	1.90		1 <sup>b</sup>		21.62	3.40	3	H =	16.69	10.24	4	H =
slow	13.86	10.01	5	u = 6	16.83	10.80	9	5.46	15.77	10.24	14	9.01
Moderate	6.29	8.53	6	ns	4.71	8.95		(*)	5.44	8.43	13	*
Fast			0 <sup>b</sup>				\$		-		0 <sup>b</sup>	

<sup>a</sup> F for analysis of variance; H for Kruskal-Wallis test; U for Mann-Whitney U-test. ns means  $p > 0.1$ ; (\*) means  $0.1 \geq p > 0.05$ ; \* means  $0.05 > p > 0.01$ ; \*\* means  $0.01 \geq p < 0.001$ ; \*\*\* means  $p < 0.001$ .

<sup>b</sup> Excluded from statistical analysis due to small sample size.



**Table 51.** Correlations between water depth and the various surfacing, respiration and dive variables September 1985-86.

	Spearman Rank Correlation	n	p <sup>b</sup>
<b>Mean Blow Interval<sup>a</sup> vs. Depth</b>			
Presum. Undisturbed	<b>0.225</b>	330	<b>***</b>
Potent. Disturbed	<b>0.263</b>	<b>137</b>	<b>**</b>
<b>All</b>	<b>0.280</b>	<b>467</b>	<b>***</b>
<b># Blows/Surfacing vs. Depth</b>			
Presum. Undisturbed	0.441	68	<b>***</b>
Potent. Disturbed	<b>0.674</b>	55	<b>***</b>
<b>All</b>	0.484	123	<b>***</b>
<b>Duration of Surfacing vs. Depth</b>			
Presum. Undisturbed	<b>0.436</b>	<b>114</b>	<b>***</b>
Potent. Disturbed	0.595	<b>78</b>	<b>***</b>
<b>All</b>	0.458	<b>192</b>	<b>***</b>
<b>Duration of Dive vs. Depth</b>			
Presum. Undisturbed	<b>0.539</b>	<b>28</b>	<b>**</b>
Potent. Disturbed	<b>0.642</b>	32	<b>***</b>
<b>All</b>	0.575	60	<b>***</b>

<sup>a</sup> Mean of all blow intervals within a given surfacing.

<sup>b</sup> \*\*means  $0.01 > p > 0.001$ , and \*\*\*means  $p \leq 0.001$ .

Although doubtful cases were excluded, all estimates were approximations. Also the estimates are net straight-line values in the horizontal plane. For some whales, the results undoubtedly underestimate the actual horizontal distance travelled, and in all cases they exclude the vertical distance travelled. We have almost no information about the underwater paths of the heading from that when they dove, indicating that their underwater paths were not straight lines. We also do not know how deep they dove, except on the one occasion on 5 September 1986 when we saw a whale surfacing with mud brought from the bottom.

Estimated distances travelled during dives ranged from 0 to 700 m during dives of duration 0.3 to 30.7 min (Table 52 and Richardson et al. 1986b, p. 213). During observation sessions when non-calf whales were classified as feeding in the water column, the average distance travelled during 17 dives was  $337 \pm \text{s.d. } 203$  m, and the average duration of those dives was  $17.3 \pm 8.05$  min. There was a non-significant tendency toward a correlation between distance travelled and dive duration ( $r = 0.29$ ,  $n = 17$ ). If we consider 10 additional dives during observation sessions when there was some surface feeding, bottom feeding, or traveling as well as water-column feeding, the

Table 52. Estimated distances travelled underwater during dives by individually recognizable bowheads, September 1986. See Richardson et al. (1986b, p. 213) for corresponding 1985 data.

Predominant Activity During observation session	Observation session	Whale Status	Est. Distance Travelled (m)	Duration of Dive (rein)
<b>Presumably Undisturbed</b>				
Water-Col. Feeding	8 Sept	Small	275	8.9
	15 Sept	Mother & Calf	c. o	(6.3) <sup>b</sup>
	"	Mother & Calf	200	(8.7) <sup>b</sup>
	"	Mother & Calf	400	6.3
	"	Mother & Calf	250	(17.5) <sup>b</sup>
	"	Calf	250	(3.0) <sup>b,c</sup>
	26 Sept C	Calf	500	(19.3) <sup>b,c</sup>
Bottom and water-cm Feeding	5 Sept	Small	350	(2.5) <sup>b</sup>
	"	Small	350	(11.1) <sup>b</sup>
	"	Small	300	(11.5) <sup>b</sup>
	"	-	40	(1.1) <sup>b</sup>
	"	-	70	(1.3) <sup>b</sup>
surface and water-al. Feeding	14 Sept		350	17.5
	16 Sept	Large	550	25.6
Log Playing	22 Sept A	Small	c. o	0.3
	"	Small	c. o	0.5
<b>Potentially Disturbed</b>				
Water-Col. Feeding	26 Sept C	Calf	[c. 100]	[30.9] <sup>a,c</sup>
	"	Calf	500	12.1 <sup>c</sup>
	"	Calf	150	3.5 <sup>c</sup>
Mother-Calf Interactions	15 Sept	Calf	c. o	(11.3) <sup>b</sup>
Socializing	26 Sept A		[300]	[34.3] <sup>a</sup>
			[300]	[34.9] <sup>a</sup>

<sup>a</sup> One or more surfacings were missed; distance estimated is net distance during the stated interval.

<sup>b</sup> Dive duration is approximate.

<sup>c</sup> Water-column feeding probably only by the mothers of these calves, not by the calves.

\* Same whales.

averages are  $303 \pm 194$  m and  $14.8 \pm 9.09$  min ( $n = 27$ ); the correlation between distance and dive duration was stronger, at  $r = 0.46$ ,  $n = 27$  (significant at  $p < 0.01$ , 1-sided comparison).

These figures **should** not be 'extrapolated to other situations. Migrating **bowheads** and other actively traveling **bowheads** sometimes travel considerably farther **than** 700 m **during** a dive (e.g. Koski and Johnson in prep.). No estimates were obtained for **whales** whose **only** activity was traveling, largely because **most whales** suspected to be traveling westward were apparently engaged in feeding at **the** same time.

summary: Surfacing, respiration and diving behavior of bowhead **whales** during September **of** 1985 and 1986 was generally similar to that recorded during previous summer and autumn studies. Durations of surfacings, durations of dives, and number of blows per surfacing were positively correlated with one another and with water depth.

Blow intervals and (less consistently) durations of surfacings differed significantly between whales that were undisturbed **vs.** those exposed to noise pulses from distant seismic vessels. However, in the case of duration of surfacing, the direction of the trend was inconsistent with that observed during previous more detailed work. We suspect that at **least** some of the apparent trends were actually in response to naturally varying factors.

**Blow** intervals and durations of surfacings and dives **of bowheads** feeding in shallow **waters** near Komakuk (along the Yukon coast) averaged slightly **less than** those **of** bowheads in and **near** the **official study** area. This was probably a **result** of the shallower average water depth at observation locations near Komakuk, since **all** of these variables are correlated with water depth. **Blow** interval was longest for whales engaged in water-column feeding or **travelling**, and duration of surfacing was **longer** for whales engaged in surface feeding or traveling than **for whales** engaged in other activities. When bowheads were feeding in the water **column**, net distances **travelled** during **single** dives ranged from about 0 to 700 m, and averaged about 300 m.

Other Behavioral Variables. --Undisturbed and potentially disturbed bowheads did **not** differ significantly in their speeds of movement, frequency of turns **while** at the surface, frequencies of **pre-dive** flexes, and frequencies of fluke-outs before dives. However, amount of social **activity**, when whales were actively interacting, was higher during potentially disturbed than at undisturbed times (21% vs. 11% of surfacings). **Aerial activity** (breaches, tail and flipper slaps), although rare overall, **also** occurred **slightly** more often during potentially disturbed than undisturbed **times** (4% vs. <1% of surfacings; Table 53).

Undisturbed whales raised their flukes above **the** water surface during a greater proportion of dives when engaged in suspected water **column** feeding **than** when surface feeding (62% vs. 27%; Table 53). Interestingly, **pre-dive** flexes occurred more often during surface feeding than suspected water **column** feeding (53% vs. 33%). **Flexes** may occur often during surface feeding when **whales** raise their **heads** higher than **their** mid-bodies in order to feed as close as possible to the surface.

Table 53. Contingency tables for categorical behavioral variables, September 1985-86. Units of observation are surfacings. Calves are excluded.

Social Activity	Potentially Disturbed	Presumably Undisturbed	Aerial Activity	Potentially Disturbed	Presumably Undisturbed
None	138	369	None	192	479
Yes	36	46	Yes	9	3
% Yes	(21)	(11)	% Yes	(4)	(<1)
$\chi^2=9.4$ , df=1, p<0.01			$\chi^2=12.2$ , df=1, p<0.001		
Flukes Out on Diving*	Water Column Feeding	Surface Feeding	Pre-Dive Flex*	Water Column Feeding	Surface Feeding
No	43	43	No	54	17
Yes	70	16	Yes	26	19
% Yes	(62)	(27)	% Yes	(33)	(53)
$\chi^2=18.8$ , df=1, p<0.001			$\chi^2=4.3$ , df=1, p<0.05		
Pre-Dive Flex*	Nearshore Komakuk Area	Official Study Area	Flukes Out on Diving*	Nearshore Komakuk Area**	Official Study Area**
No	96	86	No	47	21
Yes	68	25	Yes	20	34
% Yes	(41)	(23)	% Yes	(30)	(62)
$\chi^2=10.6$ , df=1, p<0.01			$\chi^2=12.5$ , df=1, p<0.001		
"Turn During Surfacing*	Nearshore Komakuk Area	Official Study Area	Speeds of Movement*	Nearshore Komakuk Area	Official Study Area
No	58	21	None-Slow	96	51
Yes	43	31	Mod-Fast	54	48
% Yes	(43)	(60)	% Mod-Fast	(36)	(48)
$\chi^2=4.0$ , df=1, p<0.05			$\chi^2=3.84$ , df=1, p=0.05		

\* Presumably undisturbed whales only.

\*\* 1985 data only.

Undisturbed whales also showed **pre-dive** flexes more often in the **Komakuk** area than in the official study area (**41% vs. 23%; Table 53**), and we surmise that this was due to the occurrence of surface feeding in the **Komakuk** area. Although undisturbed whales **fluked** out more often in and near the official study area than **in shallow water close to Komakuk** in 1985 (**62% vs. 30%;  $\chi^2 = 12.5$ ,  $df = 1$ ,  $p < 0.001$** ), this was not evident in 1986, nor in 1985-86 data combined. Significantly more reorientations (or 'turns') occurred **while** whales were **in the** official study area than in the **Komakuk** area (**60% vs. 43%; Table 53**). This may have been due to the significantly **longer** surface times in the official study area than **in the Komakuk** area (**means of 1.57 min vs. 1.02 min**, see **Table 48**), allowing greater time for whales to initiate turns.

Our summer work showed that pre-dive flexes **tend to be associated with** fluke-outs, but occur less often (**Würsig et al. 1985a,b**). We found the same trend **in** September 1985-86. Pre-dive flexes occurred more often in September 1985-86 than during August **1982**, a month for which comparable data exist (**pre-dive** flexes preceded 24% of dives in Aug **1982** vs. 34% of dives in Sept **1985** and 1986; Aug 1982 data from **Würsig et al. 1985a**). **In 1982**, pre-dive flexes were more common in **late** August than in **early** August; the 1985-86 data suggest that the increasing trend extends into September. We do not know why this is so, but a general decrease in social activity from summer to **fall** may be at least partly responsible.

**Whales tended** to move **faster** in and near the official study area than off **Komakuk**. The percentages of surfacings with moderate or fast speeds were 48% and 36%, respectively ( $p = 0.05$ , **Table 53**). This is consistent with the fact that several identifiable whales were **resighted at Komakuk** over periods of several days in both years. **In contrast**, there were **no** confirmed between-day **resightings** in and near the study area in **1985** (Fig. 133), and none other than those close to the **Kongakut** Delta in 1986 (Fig. 134).

We observed **whales** playing with **logs** **once** on 22 September and three times on 26 September 1986. On 22 September a **small whale** associated with a **log** for at least  $\frac{1}{2}$  h. On the 26th a **young male** (identified to sex as it rolled ventrum up) pushed and nudged a **log** for at least 16 min. Later in the day a **female** pushed, nudged, and often balanced on her back a **log** for at least 44 min; and finally on that day, a **calf** associated with a **small log** for at least 7 min while its mother was apparently diving. The calf and mother were **later** seen together, and the calf was observed nursing.

Log playing has been seen sporadically during summer and autumn (**Würsig et al. 1985a,b; D.K. Ljungblad, pers. comm.**), and calves have **also** been seen playing with other debris in summer (**Würsig et al. 1985a,b**). Association with objects has been described for other whales, including humpback whales (**Couch 1930**), right whales (**Payne 1972**), gray whales (**Swartz 1977**), and many toothed whales. We assume that **log** and other play by individual whales is a form of entertainment by lone animals, perhaps at times in lieu of socializing with conspecifics. It is **also possible** that **object manipulation, especially by calves**, provides practice in **skills** associated with socializing and perhaps with feeding.

## Discussion

### Numbers of Feeding Bowheads Present

Some bowhead whales feed in the southern part of the study area during **late summer** or early autumn in most if not **all** years. However, the amounts, locations and timing of feeding vary from year to year. Prior to this study, bowheads that were believed to be feeding were seen within the continental shelf portion of the study area each September from 1979 to 1984 (Fig. 109 on p. 260; Ljungblad et al. 1986a). Most of these feeding whales were in the southeastern part of the study area, but a few were north of **Kaktovik**. **Stomachs** of almost **all** whales taken during autumn near **Kaktovik** contain **zooplankton** (Lowry and Frost 1984; Lowry et al. 1987).

Utilization of the study area was **less** intense in **1985** than in most other recent years, including 1986, **In 1986**, the southeastern corner of the official study area was within the western edge of the late summer feeding range of the population. In early September 1986, feeding whales extended west along the coast to the **Kongakut Delta**, just west of the Canadian border (**141°50'W** longitude). At that time in **1985**, the western edge of the feeding range was about 40 km farther east, just east of the Canadian border. Although feeding bowheads were quite conspicuous **in the Kongakut Delta area in 1986**, they were concentrated into a small area and the number of whales present was not large. We estimate that, in early September 1986, about 50 bowheads were feeding within the southeast part of the study area. In both 1985 and 1986, many more bowheads fed **in coastal waters** farther east, **along** the Yukon coast, but these whales were not **in** the Eastern Alaskan study area.

Besides the difference in the western extent of the coastal feeding area between 1986 and 1985, utilization of waters farther offshore over the continental shelf was **also** greater in **1986**. More whales were **seen** over the **middle** and outer shelf in mid September of 1986 than at the same time in 1985. Most of these whales were not traveling strongly westward, although some westward movement did occur as **early** as early September 1986, particularly in deep waters. Westward migration through the middle shelf portion of the study area became conspicuous in **late** September of both 1985 and **1986**, but even then many of the whales were feeding part of the time.

The apparent low abundance of whales in the study area during 1985 was **at least** partly a **real** phenomenon, but may **also** have been partly a result of low detectability of whales after ice moved into the area in mid September 1985. The virtual absence of **whales** before mid September 1985 was real; early September surveys were conducted under good conditions with **almost no ice**. However, most of the study area was >90% covered **by** pack **and/or** new ice after **17 September in 1985**. The behavioral and sighting data used to derive our correction factors for missed whales came from areas with much open water. Detectability of bowheads during surveys over areas with much ice has not been measured. Under some types of ice conditions detectability may be as high or higher with ice as **in** open water (McLaren et al. 1986); **in** other types of ice detectability may be considerably **lower** than **in** open water. We suspect that numbers of whales migrating through the study area after mid September **in 1985** were underestimated. However, detectability of the **bowheads feeding** in the study area **in** late September 1985 was probably **little** (if any) lower than **that** indicated by the behavioral observations, and **little** if any lower than that **in**

other years. The feeding whales were in the few areas with considerable open water, and those areas were surveyed intensively. For further discussion of detectability in 1985, see Richardson et al. (1986b, p. 179-181 and 214-215).

Utilization of the study area in August was not studied during this project, but has been observed by Ljungblad et al. (1986a-c). Small numbers of bowheads have been seen in the Eastern Alaskan Beaufort Sea in August of some years. Most of these whales have been in deep waters over the continental slope (Fig. 107A). Although whales have sometimes been seen in the same part of the study area over a period of several days during August, none of these whales have been specifically recorded as feeding. Consistent with earlier years, a few bowheads were seen within the official study area in August 1985-86 (Ljungblad et al. 1986c, in prep.). Most were over the continental slope, and most were near the eastern edge of the study area, east of 141°W (Fig. 112-113, 121).

Utilization of the study area in October also is not well documented. Our field seasons ended on 3 October 1985 and 27 September 1986, before the end of migration. In most years NOSC's October surveys in our study area have been limited because their October survey coverage has been concentrated farther west. Based on 1985-86 and earlier data, the peak of westward migration through the study area is normally in mid-late September (Johnson 1984; Ljungblad et al. 1986b,c; this study). However, some whales remain in the Canadian Beaufort Sea until early-mid October (Evans and Holdsworth 1986; Harwood and Norton 1986). In 1985, bowheads continued to pass through the study area in early-mid October. The numbers seen were very low, but this was at least partly a result of limited survey coverage and {perhaps} the heavy ice cover. In 1986, westward migration past Kaktovik continued at least through early October (Moore et al. 1987'), but the numbers passing are unknown, as is the date when the 1986 migration through the study area ended. Whales present late in the migration season probably feed less often than those present earlier. Whales seen late in the season are usually swimming steadily westward. The late migrants often travel west "in heavy ice conditions, although this was not the case in 1986.

To summarize the occurrence of feeding in the Eastern Alaskan Beaufort Sea, some feeding whales occur there during September of most if not all years. A limited amount of feeding may also occur there in August and October, but this has not been documented conclusively. Whales present in August tend to be farther offshore than those present later in the season. The locations, amounts and timing of feeding within the study area vary from year to year. However, within the Eastern Alaskan Beaufort Sea, the main feeding area is the continental shelf, and the main feeding period is September. The western edge of the main late summer feeding range is within the Eastern Alaskan study area in some years, like 1986, and just to the east of that area in other years, like 1985. However, even in the latter types of years, some whales feed within the Eastern Alaskan Beaufort (and farther west) as they migrate westward in mid-late September.

#### Mothers, Calves, and Population Segregation

Many if not all bowhead calves born during the spring or early summer continue to accompany their mothers during the autumn migration through the Alaskan Beaufort Sea. In September 1985-86, calves were 6-7½ m long, although

not all bowheads 7-7½ m long were calves. Mothers were observed feeding **in** and near the study area on several occasions **during** September 1985-86. Mothers and **calves** have been seen throughout the August-October period, and in waters of all depths (Tables 37, 38; Fig. 129).

The **photogrammetric** data, on the other hand, showed that there were marked and consistent differences in the percentage composition of **the** whales at different locations in and near the study area. The whales present **well** offshore **during late** September 1985-86 included a **wide** variety of sizes, including calves, **subadults** and adults (**Fig. 130-132**). Numbers of adult-sized whales (**>13 m long**) and calves were proportionately **higher**, and proportions of **subadults lower**, than are often found on the summering grounds (cf. Davis et al. 1983, 1986a,b; Cubbage et al. 1984; Cubbage and Calambokidis 1987a,b). We found that 44% of the whales in offshore areas were **>13 m long** (Table 39). In contrast, whales **along** the shore near **Komakuk (1985)** and the **Kongakut Delta (1985-86)** were predominantly **subadults**; only 5% were **>13 m long** (Table 39). Although a few mother-calf pairs were found close to shore, mothers and calves made up a much lower proportion of the whales in nearshore than **in** offshore areas.

During the summers of 1983-86, bowheads close to **the** Yukon coast east of Herschel Island were also predominantly **subadults** (Würsig et al. 1985b; Cubbage and Calambokidis 1986, 1987a; Davis et al. 1986a,b). In contrast, **large** bowheads are common far to the east in Franklin Bay and Amundsen Gulf. Our **within-** and between-year refighting data show that at least some of **the** large adult whales that migrate through the middle shelf portion of the study area **in** late September summer far to the east. In **contrast**, some of the **subadults along** the coast **in** and near the study area have also been sighted **in** the same or earlier years along the coast east of Herschel Island. It is noteworthy that large concentrations of **subadults** do not occur along the Yukon coast in **all** years; for example, they were absent **in** 1980-82 (Richardson et al. 1985a, 1987). **Photoidentification** data show that at least a few of the subadults near the Yukon coast in the late summers of 1984-85 had been in deeper water off the Yukon coast in **the** late summer of 1982 (Davis et al. 1986b, p. 170-172).

#### Feeding Areas

In previous years, bowheads known or suspected to be feeding have been observed at many locations within the continental shelf portion of the official **study** area (Fig. 109 on p. 260). In 1985, the only part of that area where much feeding was observed was 30-40 km north and northeast of **Kaktovik** in late September. Most feeding in that area was in the water column well below the surface, but some near-surface feeding was observed on 29 September. Feeding bowheads had **also** been observed in that area in late September of 1983-84 (Fig. 109). Our only other observation of feeding bowheads within the official study area in 1985 was **close** to shore at **142°W** on **19** September, where 2-3 **whales** appeared to be feeding in the water column. Just east of the official study area, many **subadult** whales fed **in** shallow water **along** the Yukon coast **in** August and September 1985, and both **subadults** and adults fed **well** offshore north of **Komakuk**.



In 1986, whales fed along the coast as far west as the Kongakut Delta ( $141^{\circ}50'W$ ), about 40 km farther west than in 1985. Most of this feeding was in the water column, not at the surface. Zooplankton sampling showed that dense concentrations of the small copepod Limnocalanus macrurus were present at mid-water or near the bottom at the feeding locations off the Kongakut Delta (see 'Zooplankton and Hydroacoustics' section, p. 187-199). This nearshore feeding area was only used for a few days in early September. In contrast, the Yukon coast east of the official study area was again used for several weeks during August-September. There are no previous definite reports of bowheads feeding close to the Kongakut Delta. However, whales fed equally close to shore slightly farther east, at Demarcation Point, in 1979 (Fig. 109; Ljungblad et al. 1986a). Also, on 22 September 1982 many bowheads were present close to shore from the Canadian border west to Beaufort Lagoon, including the Kongakut Delta area (Johnson 1984); some of them appeared to be feeding (S.R. Johnson, pers. comm.).

Many of the whales that travelled west through the middle shelf region in late September 1986 also appeared to be feeding in the water column. Some of these observations were offshore from Komakuk--just east of the official study area and not far from locations where feeding had been seen in late September 1985. Other cases were within the southeast part of the official study area. Feeding was also common in middle shelf waters of the SE part of the study area in mid-late September of 1981-82 (Fig. 109; Ljungblad et al. 1983, p. 87-92; 1986a; Fraker et al. 1985).

The predominance of water-column feeding over other feeding modes within the official study area was consistent with observations in previous years. Near-surface feeding has rarely been observed in this area, and the only report of near-bottom feeding (as evidenced by mud brought to the surface) was our one observation off the Kongakut Delta (5 Sept 1986). The predominance of water-column over near-surface feeding was consistent 'with the very low biomass of zooplankton in surface waters within most parts of the study area in September 1985-86. Zooplankton biomass was usually much higher in one or more 'layers' of plankton, each 5-10 m thick, at depths between 10 and 40 m (see 'Zooplankton' section). Bowheads feeding in the water column presumably concentrated their feeding in those layers. In nearshore and inner shelf waters, the densest layers of plankton were often close to the bottom (e.g. Fig. 98 on p. 218). At least some of the bowheads that bring mud to the surface are probably whales that contact the bottom while feeding on zooplankton concentrations just above the bottom.

Feeding bowheads were found more commonly just east of the official study area than within it, especially in 1985. Bowheads were present for several weeks during both 1985 and 1986 in shallow waters (<15 m) along the Yukon coast near Komakuk. They fed near the surface as well as in the water column. Bowheads had also been present and feeding along the coast near Komakuk at corresponding times in 1984 (Richardson et al. 1985a; Ljungblad et al. 1986a). In all three years, most bowheads feeding in shallow water near Komakuk were subadults (Table 39). Previous to 1984, no concentration of feeding whales had been noticed near Komakuk. At least in 1983, survey coverage during late summer was sufficient to show that no concentration of whales was present there (Richardson et al. 1984, 1985a).

The only data on food availability close to shore near Komakuk are our limited results from 4 and 7 September 1986 (Fig. 83, 86 on p. 190, 196). Most zooplankton biomass was at mid-water or near the bottom. However, **zooplankton** abundance is occasionally high in surface waters close to arctic shorelines during **late** summer {see Bradstreet and **Fissel** 1986}. The cases of near-surface feeding that we observed probably involved such occasions.

The behavior of the whales that fed in the official study area in 1985-86 was similar to behavior during previous summer and autumn observations of water-column feeding (cf. **Würsig** et al. 1984, 1985a,b). Brief surfacings were interspersed between **long** dives, and net motion during dives was generally no more than a few hundred meters. However, during some observation sessions in **late** September, headings were predominantly westward when the whales surfaced between feeding dives. This suggests that the whales feeding within the official study area in late September 1985-86 were traveling gradually west rather than remaining in one specific location. The lack of resightings of individually recognizable **whales** in the middle-shelf region in late September also suggested that individual bowheads did not linger for long at feeding locations in that area.

Feeding locations in and near the Eastern Alaskan Beaufort *Sea have* differed among years (Fig. 109; this study). Certain areas were used by feeding whales in more than one year, but feeding has not been observed in any one area in all years when **it was** surveyed. Although variations in ice cover may have some influence on areas used for feeding, utilization of ice-free areas also differs from year to year. For example, the Kongakut Delta area was largely ice free in **early** September of both 1985 and 1986, but bowheads were present **only** in 1986. Thus, we must look to factors such as variation in food availability in the Eastern Alaskan and Canadian sectors of the Beaufort Sea for an explanation of **the** year-to-year differences in feeding locations (see 'Integration' ).

#### Residence Times

The **whales** (mainly **subadults**) that fed along **the** Yukon coast near **Komakuk** from mid August to late September in both years included some individuals that were present repeatedly (if **not** continuously) for lengthy periods. Periods between first and last sightings were 1 to 16 d, averaging 7.6 d (n = 11). These figures underestimate the maximum and average residence times, since **whales** near **Komakuk** were photographed on only 6 d in 1985 and 7 d in 1986, and only a fraction of those present were photographed on any one day. Thus, the re-identification data from the Komakuk area showed that some **individual** bowheads **utilized** a specific feeding area close to the official study area for prolonged periods. These individuals presumably acquired a significant fraction of their annual energy intake in that one location. Furthermore, one bowhead photographed in nearshore waters off **Komakuk** on **two** dates in 1986 had also been photographed there on two dates in 1985.

Whales utilized waters off the **Kongakut Delta** for several days in early September 1986 (Fig. 127). Although this area was **not** used for nearly as long as was the **Komakuk** area, we confirmed that some individual **whales** were present 1-2 d after they were first photographed. **Zooplankton** sampling on 5 September, just after these whales **were** first photographed, disturbed the **whales** and caused them to swim at least several kilometers offshore away from the feeding

**area.** Whales had returned to the same feeding location by the next day (6 Sept), including at least three of those photographed there the previous day. The whales were again exposed to boat maneuvers during zooplankton sampling on the 6th. At least three more of the whales present on the 5th were feeding about 10 km farther east on the 7th (Table 41; Fig. 134). These data show that at least some of the whales feeding off the Kongakut Delta had sufficient affinity for their specific feeding location that they returned to it after being displaced by vessel disturbance. We do not know whether the repeated zooplankton sampling off the Kongakut Delta (5,6,7 Sept; 13-m diesel-powered boat) was responsible for the ultimate departure of whales from that area. Food availability in that area after 7 September is not known.

Although some individual bowheads fed in specific nearshore areas for periods of at least several days, we obtained no evidence that specific whales remained in any one offshore area for comparable periods. There were no between-day re-identifications of whales north and northeast of Kaktovik in 1985, or north of the Komakuk-Demarcation Bay area in 1985 or 1986. In contrast, some of the whales seen in these areas were seen earlier in the season well to the east, or in one case 4 d later well to the west. This evidence, although not conclusive, suggests that there was rapid turnover of the bowheads present in middle shelf (and deeper) waters during late September. Although we did observe whales feeding in these areas, it does not appear that individual whales fed for very long in any one offshore area.

#### Importance of the Study Area for Feeding

Results from this and other studies showed that few bowhead whales fed within the official study area at any time during the late summer or autumn of 1985. After the aerial survey data were corrected for submerged and other missed whales, the calculated number of 'whale-days' within the study area was low--possibly about 1400 in early-mid August and 2800 during the migration period in September and October. These values are very approximate because of the low sample sizes and extreme degree of extrapolation involved. However, the 2800 estimate for the migration period is lower than the 4400-7200 expected if the Western Arctic population had migrated steadily westward through the study area at 5 km/h without stopping to feed. (The 4400 value is based on an approximate transit time of 1 day and the most recent published population estimate [I.W.C. 1986]; the 7200 value is based on a recent revision of the population estimate [I.W.C. in press].) In fact, at least a few whales did stop to feed in the study area in late September 1985. Thus, the 2800 'whale-days' figure was probably underestimated, perhaps by a factor of x2 or more. Whales migrating through areas covered by heavy pack ice were probably even less conspicuous than our correction factors assume. Even so, the number of whale-days of feeding within the study area in 1985 was very low. This conclusion would be true even if bowheads fed as they swam westward, as our behavioral observations on some dates suggested.

It should not be assumed that the entire Western Arctic bowhead population travelled through our study area during August-October 1985. Some probably travelled westward north of the 2000 m contour, and some may have remained north or west of the study area throughout the 'summer of 1985 (cf. Davis et al. 1986b). Thus, one would not necessarily expect a minimum of 4400-7200 whale-days of utilization of the official study area. However, it is unlikely that avoidance or 'by-passing' of that area was the main reason for

the apparent scarcity of bowheads there in 1985. Numerous bowheads were detected in Canadian waters during early-mid September of 1985 (Davis et al. 1986b; Norton and Harwood 1986). In Mackenzie Bay alone, several hundred bowheads were present in early September 1985. Some remained there well into October (Evans and Holdsworth 1986). These whales presumably migrated through our study area under heavy ice conditions in late September or October 1985. Indeed, this was confirmed by **photoidentification** in a few cases (Fig. 133).

In 1986, total utilization of the study area was estimated as about 3400 whale-days in **August** (probably an **overestimate**), 8550 whale-days in September, and an unknown amount in October. If utilization in October was 1000 whale-days, then the calculated utilization during the September-October period was about 9550 whale-days in 1986, as compared with 2800 in 1985. Assuming a population of about 4400 whales, an average whale was apparently in the study area for at least 2-3 d in the late summer of 1986, and perhaps 3-4 d if there was significant utilization in August or October. Assuming a population of 7200, the corresponding figures were at **least**  $1\frac{1}{2}$  d, and perhaps **2-2 $\frac{1}{2}$**  d.

Although some bowheads are seen in the study **areain** August and early September, the majority remain in Canadian waters at those times. Results from several years of surveys have shown that some bowheads regularly remain as far east as Franklin Bay, 550 km east of the Alaska-Yukon border, **until** early-mid September (see Richardson et al. 1985a for review). In 1981, there was a major effort to survey the entire summer range and **to** correct the aerial survey results for missed whales (Davis et al. 1982). In that year, the majority of the population was accounted for in Canadian waters on 7-14 September, even though it was not possible to survey all "Canadian waters where bowheads were known or expected to occur. The Canadian results, **along** with data on the timing of peak migration through Alaskan waters in various years (p. 257; Johnson 1984; Ljungblad et al. 1986b,c), show that most bowheads do not move into the Eastern Alaskan **Beaufort** Sea before mid September.

At least a few bowheads remain in Canadian waters **until** early or even mid October (Ljungblad et al. 1983, 1985a, 1986c; Evans and Holdsworth 1986; Harwood and Norton 1986). The numbers that do so are not **known because**, before 1985, there had been almost no survey coverage of the Canadian Beaufort Sea after mid September. Ice conditions in the Alaskan Beaufort Sea worsen rapidly in October, and very few bowheads remain there after mid October (Ljungblad et al. 1986c). The last sightings in the official study area in 1980-84 were on 21 September-10 October (see p. 257). The last records there in 1985-86 were on 12 and 7 October, respectively (Fig. 120A; Moore et al. 1987). Hence, the whales that remain in Canadian waters **until** October probably travel rapidly through the Alaskan Beaufort Sea without lingering to feed.

In their analysis of **trophic** relationships in the Alaskan Beaufort Sea, Frost and Lowry (1984) assumed that an average Western Arctic bowhead feeds for 25 days/year within the Alaskan Beaufort Sea. Some of this feeding would be during spring migration or in autumn west of our study area. However, the primary feeding area and feeding period within the Alaskan Beaufort Sea is believed **to** be within the study area during-late summer and early autumn (Ljungblad et al. 1986a). The average duration of feeding within the study area in the late summer and autumn of 1985 and 1986 was much **less** than 25 days. Our estimates were <1 d in 1985 and 3-4 d in 1986, **or lower** if the actual population size is greater than 4417 bowheads. Even if these figures

are underestimates, as the 1985 value almost certainly **is**, average utilization of our study area was only a **small** fraction of **25 d**.

The only **information** about the amount of time taken to travel across the Alaskan **Beaufort** Sea as a **whole** during autumn migration is the following:

1. A bowhead radio-tagged just east of the Alaska-Yukon border (15 Sept 1986) passed Point Barrow 16 d later **on 1** October (Appendix 4). We have no definite information about when this whale left the tagging **site**, but it was probably by 22 September (**cf. Fig. 127**).
- 2\* A bowhead photographed near the east edge of our study area (27 Sept 1986) had reached **Flaxman** Island, about **1/3** of the way across the Alaskan Beaufort Sea, in 4 days (Fig. 134). **Thus, this whale might** have taken 12 d to cross the Alaskan **Beaufort**.

Some of this time may have been spent feeding in and west of our **study** area. However, even without feeding or **rest**, a minimum of 5 days would be required **to swim west across** the Alaskan **Beaufort** Sea (width 600 km) at a steady rate of 5 km/h. **To assess the importance of the Alaskan Beaufort Sea as a whole** for autumn feeding, more data on migration rates, frequencies of feeding, and food availability in areas west of our study area would be necessary.

Our two-year study apparently documented utilization of the study area in a low-use year and a moderate-use **year**, but not a high-use year. The **low** degree of **utilization** of the **study** area in 1985 is obvious (e.g. **Table 30** on p. 296). Relative utilization in 1986 is more difficult to establish. However, **Ljungblad et al. (1986c, in prep.) summarized** the number of **bowheads** seen **during** September of 1979-86 in their 'Block 5', the southeastern part of our study **area**:

<u>Year</u>	<u>Survey Hours</u>	<u>No. of Bowheads</u>	<u>Bowheads per Hour</u>
1979	5.26	53	10.08
1980	10.01	10	0.99
1981	20.98*	130	6.20
1982	14.07	159	11.30
1983	4091	0	0
1984	8.77	28	3.19
1985	10.89	19	1.74
1986	17.83*	42*	2.36*

\* J. Clarke, **pers. comm.**, August 1987

These **values** take into account, **NOSC's** 'connect' and 'search' surveys as well as the randomized transects considered in **Table 30**. Caution is necessary in interpreting these data because of year-to-year differences in survey strategy and survey conditions; Also the lack of distinction between feeding vs. other **whales** is a complication. In particular, the number of sightings per unit effort in 1986 seems surprisingly **low**. Nonetheless, **these NOSC** results suggest that bowheads can be more abundant in the **study** area than was documented in 1985-86. In 1982, a year with extensive survey coverage, **NOSC** detected many

more whales per unit effort than in 1985-86. On 22 September 1982, 128 bowheads were actually seen during a brief survey of part of the southeast corner of **the** study area (Johnson 1984)--many more *than we saw* within **the** official study area during any one flight in 1985-86;

Thus, the number of 'whale-days' of utilization of the Eastern Alaskan Beaufort Sea appears to **be** higher in some years than occurred in 1986. Whether the amount of feeding in the study area in those years is correspondingly greater is not known.

### Conclusions

1. A few bowheads were seen in **the** Eastern Alaskan study area by other investigators during August 1985-86, most in waters over the outer continental 'shelf and continental slope near the eastern edge of the study area. Bowheads fed along the Yukon coast **just** east of the study area in August of both years, but these whales did not extend into Alaskan waters in August.
2. The 1985 migration through the study area began around 11 September, and apparently peaked in late September after much ice was blown into the study area. At least some of the whales migrating through mid-shelf waters in late September fed briefly. Some **bowheads** continued to travel westward through the study area, in heavy ice conditions, during early to mid October 1985.
3. More whales were in the study area during early-mid September in 1986 than in 1985, including a concentration of feeding whales close to shore off the **Kongakut Delta** in the **SE** corner of the study area. The latter area was the westernmost of several feeding locations along the Yukon and Alaskan coast. Westward migration began in early September 1986, and probably peaked in late September. Migrating whales **were** closer to shore in mid- and **late** September than in early September. Migration continued into October 1986, after our fieldwork ended.
4. In 1985, raw density estimates from aerial surveys of the continental **shelf** and slope zones were very **low, only** about 0.06 and 0.04 **bowheads/100 km<sup>2</sup>**, respectively, during mid-late September. These figures are very approximate because of the low number of sightings. In 1986, estimated densities in the **shelf** zone during September (excluding the feeding area off the **Kongakut Delta**) were considerably higher, ranging from 0.21 to 0.33 **bowheads/100 km<sup>2</sup>**; the estimated raw density over the continental slope was 0.12 **bowheads/100 km<sup>2</sup>** in early September, but zero thereafter. Limited coverage of the northern part of the **study** area (depths >2000 m), mainly by the Naval Ocean Systems Center, revealed no **bowheads** in either year; a few bowheads have been seen there in earlier years.
- 5\* Behavioral data indicated that **only** about 12-14% of the bowheads present 'on-transect' during this study were potentially detectable during standard aerial surveys; whales were submerged and invisible **almost** 90% of the time. The available data from 1981-84 suggest **that** detectability of **bowheads** in and near our study area was similarly

low in those earlier years. Detectability was apparently even lower for whales in areas of heavy ice cover, e.g. in late September 1985.

6. Even after allowance for the many **whales** present but undetectable **during aerial** surveys, estimated numbers **in the study area in 1985** were very **low**, estimated as **<100**, at **all times during** late summer **and early** autumn, Higher numbers, estimated as **220-370**, were present **at various times** in September **1986**. Utilization of the study area in August-October was estimated as **about** 4200 whale-days in 1985 and **13,000** whale-days in 1986. The **1985 value** may be an underestimate, **given** that it is barely adequate **to account** for steady **westward** migration of a population of 4417 whales across the **study area**, and inadequate if the population size is about 7200.
7. Mother-calf pairs sighted within the study area during 1985-86 were widely distributed geographically and temporally, as in previous years.
8. Many feeding bowheads lingered along the Yukon coast near **Komakuk**, **10-50** km east of the official study area, during late August and much of September 1985-86. Several individually recognizable whales photographed near **Komakuk** were **re-photographed** on **later** days and/or the next year. Minimum residence times averaged **7.6 d** ( $n = 11$ ), with a maximum documented period of **16 d**. Most bowheads in this nearshore area in **both** years were **subadults 7-13 m long**, but a few **adults** were present. We radio **tagged** five **bowheads in this area in 1986**; three were detected on subsequent days **after** they had begun migrating westward through Alaskan waters.
9. The concentration of feeding whales near the **Kongakut Delta**, in the official study area, during early September 1986 was apparently a **westward extension** of the nearshore concentration farther east. Again, most whales were **subadults**. Several individuals were re-photographed 1-2 d after first being photographed but the **overall** duration of feeding off the **Kongakut Delta** was briefer than that **along** the coast farther east.
10. Late September was the only time in 1985 when a concentration of feeding **bowheads** was found within the study area. They fed some 30-40 km N and **NE** of **Kaktovik**. Similarly, many of the **whales that** were migrating through **middle shelf** waters in mid-late September 1986 were feeding intermittently. In both years, the **whales** that fed over the middle **shelf** during migration included many adults (some with calves) as **well as large subadults**, but few **small (<10 m) subadults**. These **whales** did not seem to linger **in any one area for long**; there were no between-day reidentification **at middle-shelf feeding sites**. However, several of these whales had been photographed earlier in the season (or in previous summers) in Canadian waters.
11. Most bowheads feeding within the official study area fed below the **surface**, consistent with the **low** abundance of **zooplankton** in surface waters. In contrast, bowheads often fed at the surface along the Yukon coast. Almost no **near-bottom** feeding was detected.

12. **Many** of the bowheads observed within and just east of the official study area during 1985, and to a lesser extent 1986, were exposed to faint-moderate intensity noise pulses from distant seismic vessels. Activities seemed normal despite this noise exposure.
- 13\* The behavior of bowheads feeding within and near the study area was similar to that documented during previous studies in summer and early autumn.
14. When bowheads engaged in presumed water column feeding, **net** horizontal distances **travelled** during single dives ranged from **about** 0 to 700 m, averaging about 300 m during dives of average duration 15 min. Actual distances **travelled** underwater were undoubtedly greater, thereby increasing the potential **volume** of **water** filtered.
15. During some observation sessions when bowheads were feeding, the headings of **the** whales when they surfaced to breathe were predominantly westward. This suggests that bowheads sometimes were migrating gradually westward as they were feeding.
16. Observed feeding locations in and near the Eastern Alaskan Beaufort Sea have differed between years. **No** one part of the study area has been identified **as a** consistent feeding location. The study area is apparently near the western edge of the main summer feeding range. Prior to the start of active westward migration, feeding whales extend into **the study area in** some years (**like 1986**), but not in **all** years. During the subsequent period of active westward migrations considerable feeding takes place in the study area, probably in all years.
17. Utilization of the study area for feeding varies between years, depending in part upon whether the western edge of the main summer feeding range extends west into the study area in a given year. Utilization in 1985, when the main summer feeding area did not extend into Alaska, was less than average. Utilization in 1986 was considerably greater than in 1985, but apparently **less** than occurs in some years.



**BOWHEAD WHALE FEEDING: ALLOCATION OF REGIONAL HABITAT IMPORTANCE  
BASED ON STABLE ISOTOPE ABUNDANCES\***

Introduction

To determine the importance of **the** eastern **part** of the Alaskan Beaufort Sea as a feeding area for bowhead whales, we need to know what fraction of **their** energy intake **is** acquired there. Western Arctic bowheads spend the winter and early spring in the Bering Sea (**Fig. 1 on p. 2**), when standing stocks of **zooplankton** are **at** their **annual** minima. Similarly, **zooplankton** in **the Chukchi** Sea and offshore areas of the Beaufort Sea that the **whales** traverse during the spring migration are probably **also** at annual minimum population levels. Nonetheless, a limited amount of feeding does occur **during** spring (Hazard and Lowry 1984; Lowry and Frost 1984; George and Tarpley 1986; Carroll et al. 1987; Lowry et al. 1987). **Zooplankton** stocks and energy content increase during the open water season. Much bowhead feeding has been observed in the summering areas in the Canadian Beaufort Sea (Würsig et al. 1985a,b, 1986). In addition, considerable feeding has been observed during the westward fall migration through the Alaskan Beaufort Sea (Braham et al. 1984; Lowry and Frost 1984; Ray et al. 1984; Ljungblad et al. 1986a; this study). Some bowheads migrate west across the northern **Chukchi** Sea in autumn. There is some evidence of feeding off the northeast coast of Siberia in autumn before these **whales travel** south to the Bering Sea (Marquette et al. 1982).

Despite these observations, many uncertainties exist as to the sources of **food** for bowheads. Prior to this **study**, essentially no information was available about the relative amounts of energy acquired in the various areas frequented by bowhead whales.

Parts of the Canadian Beaufort Sea may be areas of relatively high productivity (Macdonald et al. 1987). The **influx** of warm water from the Mackenzie River **melts** the seasonal ice cover and contributes both nutrients and organic matter to the coastal environment. **The large polynyas** that develop in the **Amundsen Gulf** area **allow** light energy to penetrate into a deepened **euphotic** zone that is mixed by wind **in** the spring when the rest of the southern Beaufort Sea is **still** ice-covered. Nutrients that are normally **below** the **euphotic** zone are consequently carried into the **euphotic** zone by wind mixing, allowing increased **phytoplankton** production. In addition, **upwelling** sometimes occurs along the Yukon coast and **along** the shelf break (Bradstreet and Fissel 1986; Bradstreet et al. 1987; Macdonald et al. 1987).

In the Alaskan Beaufort Sea, productivity is apparently **higher** near the Canadian border and near Point Barrow than in the intervening area (Schell et al. 1984). Near the Alaska-Canada border, the prevailing easterly winds and **the retreat of** the pack ice across a narrow continental **shelf** provide suitable conditions for **upwelling** of nutrient-rich water **during late** summer. This **upwelling** was first described by Hufford (1974) and is **detailed** by Aagaard (1981) and this study ('Water Masses', p. 82 **ff**, 129). This **upwelling** probably

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contributes to the productivity of the region **and** helps support **the** prey species consumed by bowheads **in** the Eastern Alaskan Beaufort Sea. In the western Beaufort Sea, the Bering Sea water that moves northeast around Point Barrow may be partly responsible for the high **zooplankton** stocks in that region.

By combining past measurements of primary production, ice retreat, and nutrient availability, **Schell et al. (1984)** constructed contour maps of estimated primary productivity for the **Chukchi** and Beaufort Seas. They noted an association between the higher productivity in the western and eastern Beaufort Sea and the abundance of birds, cetaceans, and pinnipeds observed **in these** areas **by** several investigators.

Primary productivity data **alone** cannot be used to determine **the** carrying capacity of the region for whales unless the food chains are defined and the efficiency of energy transfer **into whale 'food' is** known. The coupling of **phytoplankton** to **small** crustaceans such as mysids, amphipods and copepods is probably efficient **but** complete consumption of these prey by whales does not occur. Instead, most prey items may be consumed by abundant predators such as **chaetognaths** and jellyfish, which are apparently not major prey items for bowheads (Lowry and Frost **1984**). Frost and Lowry (1984) also point out that much of the biomass of small prey items ends up as food for arctic cod, *Boreogadus saida*. Cod can be viewed as direct competitors for the same food resources as the whales. Thus, the carrying capacity of the region for whales is below the superficially apparent capability projected from the annual primary or secondary productivity. This would be especially true if standing stocks of cod have increased' as a result of overharvesting of bowhead whales in the 19th century. Any attempt at estimating the importance of the **Beaufort sea** in bowhead energetic must seek to avoid the assumptions inherent **in** estimates based solely on present standing stocks of the biotic components.

### Carbon Isotopes as Tracers of Energy Flow

We sought to use the natural abundances of carbon isotopes in whales and their prey to **help** determine the regions where feeding occurs. Three isotopes of carbon are considered here: the predominant stable isotope C-12; the less common stable isotope **C-13**; and the radioisotope C-14. Almost 99% of the carbon in natural systems is C-12; about 1% is C-13. Radiocarbon (C-14) atoms are rarer, but their abundance can be measured by detecting their radioactive decay. Analyses of stable isotopes are useful in food web studies because the relative abundances of the different isotopes often vary somewhat among different areas and different prey types. Regional differences can occur as a result of differences in environmental and primary production processes.

Prior to the start of this project, **it** was apparent that the ratio of stable isotope abundances (C-13/C-12) in **zooplankton** changes progressively from west to east across the Alaskan Beaufort Sea (Dunton 1985). The C-13 isotope becomes less abundant from west to east. We hypothesized that, if this trend extended farther to the southwest and east, to the Bering and eastern Beaufort Seas, it might provide the basis for distinguishing the geographic sources of carbon in bowhead tissue.

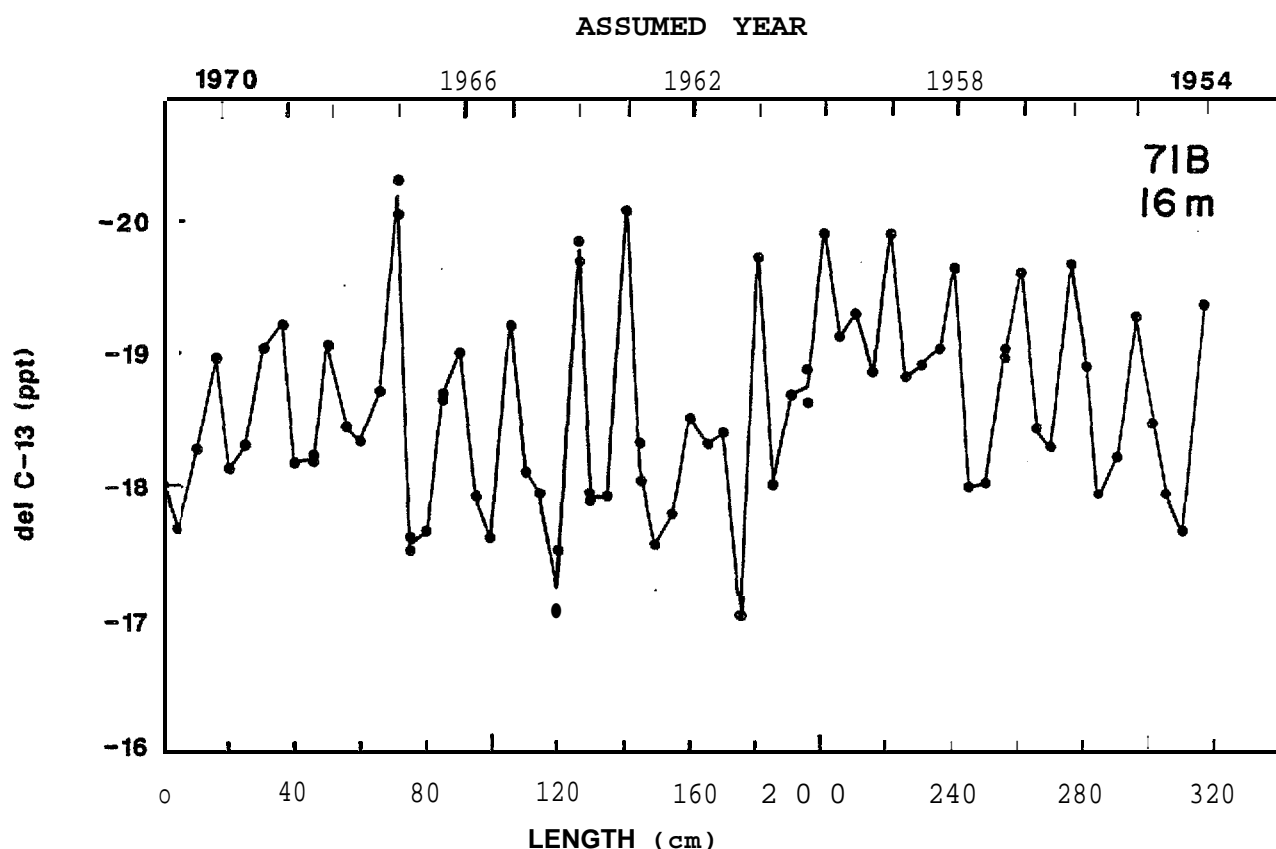
Previous work has established that the isotopic content of *prey* items is transferred conservatively into the tissues of predators (Ehleringer et al. 1986). If the **stable** isotope composition of **zooplankton** in the **Bering** differs from that in the Beaufort, then the isotopic composition of **bowhead tissue would be** expected to **differ** between autumn and spring if **bowheads** feed appreciably in winter. Conversely, **little** difference **would be** expected from autumn to **spring** if **bowheads** do not feed in winter. Before this **study**, **stable** isotope data were available from **only** a few samples of bowhead **tissue** (Schell et al. 1984; Schell 1986). The sources of these samples were **poorly** documented, and they represented only the **muscle** of **four** whales and the **blubber** of five whales. The pre-1985 data were insufficient to **allow** any conclusions about changes in stable isotope composition of **bowhead** tissue between autumn and spring.

The **C-14 (radiocarbon)** content of the whales sampled before 1985 showed considerable variation (Schell et al. 1984; Schell 1986). This indicated that some whales had fed in **upwelling** areas for at least part of the **year**. Depressions in **C-14** arise from **upwelling** of deep water into the **euphotic** zone and incorporation of C-14-depleted carbon dioxide into **phytoplankton**. This isotopic signal is also transferred conservatively through food chains and **can** be used to identify the significance of **upwelling** to the overall primary productivity of a given area.

During this project, we collected additional **zooplankton** samples from several areas **to** determine whether the trend in isotopic composition of potential prey extended across the **full** range of the Western Arctic **bowheads**. We **also** acquired samples of bowhead **muscle** and fat tissue from **whales** harvested in the spring and **autumn** of 1985-86 to determine whether the isotopic composition of bowheads differed between these seasons. An isotopic shift in bowhead whales between their fall departure from the **eastern** Beaufort Sea and their return to the **Beaufort** in spring would indicate that the animals feed actively during **late fall**, winter or **early** spring in waters west of the **sites** where **bowheads** are harvested in **fall**. If extensive feeding does occur **in** these seasons, we **would** have evidence **that** the energetic dependence of bowheads upon the eastern Beaufort Sea is **less** than presently **thought**.

#### Isotopic Composition of Baleen

This section also describes the development, during 1986, of new techniques based on the natural abundances of **stable** isotopes along the length of bowhead whale baleen. Since baleen grows from the upper jaw and is metabolically inactive once **formed**, a baleen **plate** from a large whale provides a **temporal** record of the isotopic **composition** of the energy being used over many years. In a preliminary analysis (Schell et al. in press), we found that the baleen of bowhead whales contains marked oscillations in C-13 content (**Fig. 141**). This report provides evidence that these oscillations record several aspects of the activities of the animal **for**, perhaps, **up** to 20 years in large animals and for most of the life span of younger animals (those <10 **years** old). Preliminary data on the relative abundances of the **stable** isotopes of nitrogen (**N-15** vs. **N-14**) show that the isotopic ratio of nitrogen **also** oscillates along the baleen. The present report shows that **stable** isotope analyses of baleen provide the following:



**FIGURE 141.** C-13/C-12 isotope ratios along a baleen plate from bowhead 71B, a 16 m male. Base of plate (baleen formed just before death in 1971) is at left. Year scale at top assumes that the isotope cycle is annual (see Results, later). The peaks (largest negative numbers) represent low concentrations of C-13; the troughs (smaller negative numbers) represent higher concentrations of C-13.

1. A method for determining the approximate ages of young whales, and thus a method for developing an age-length curve;
2. An approach for determining the relative time spent feeding in various habitats (as defined by the stable isotope compositions of prey) during various phases of each year represented in the baleen record;
3. Insight into the relative amounts of energy consumed in various feeding areas along the migration route.

The development of these techniques arose from an inquiry by M. Nerini of the U.S. National Marine Mammal Laboratory, Seattle, WA, about the feasibility of using the isotopic content of baleen for ageing the animals. We set out to test that feasibility based upon our findings of marked geographical variations in zooplankton isotope abundances. The findings reported here indicate that a broad suite of natural history information, beyond ageing alone, may be gleaned from the baleen.

## Objectives

In summary, the **goal** of this study was **to** use the natural abundances of carbon isotopes **in bowhead** whale **tissue** and their prey organisms to estimate the regional habitat dependencies of the whales over the **annual cycle**. To accomplish these goals, the work was divided into several **tasks**:

1. Expand the geographic and seasonal data base on **the** isotopic composition of zooplankton in regions used by bowhead whales.
2. Determine the isotopic composition **of** bowhead whale tissues taken during the spring and **fall** hunts, and compare these to determine whether there is evidence **of** appreciable feeding in winter.
3. Determine **whether** the isotopic variations along the **length** of bowhead **baleen** represent annual events, and whether they are consistent within and between different baleen plates from the same animal.
4. Document the isotopic content along the length of baleen from additional **bowheads**.
5. Evaluate regional habitat dependencies of **bowhead** whales based on **the** isotopic composition of their **prey**, their baleen, and their other tissues.

**It is** already evident that isotopes other than carbon **also** 'vary in abundance **along** bowhead baleen. Limited data on nitrogen isotopes in baleen are presented **in** this report.

These objectives constitute a major research program. This report addresses our initial findings; data are continuing to accumulate as additional **zooplankton** samples and **whale** tissue samples are acquired "and analyzed. However, the **results** presented here provides substantial start **toward** the **goal** of understanding the energetic of bowhead whales.

## Methods

### Sampling Program

**Zooplankton Samples.** --Collection locations **for** the **zooplankton** samples analyzed in this project are shown in Figure 142:

1. Southeastern Bering Sea: Samples were collected and frozen in May-June 1985 by **LGL** personnel or one of **us (SMS)** as part of **LGL's** North Aleutian **Shelf** study for NOAA and **MMS**.
2. Northern Bering Sea: Samples were collected and sorted by **Dr. R.T. Cooney** on an '**Alpha Helix**' cruise, **August 1986**. These were dried on board and no preservatives were used.
3. Bering Strait and southern **Chukchi** Sea: Samples were collected, sorted and dried by **us (SMS, NH)** on NOAA ship '**Oceanographer**', **Aug-Sept 1986**.

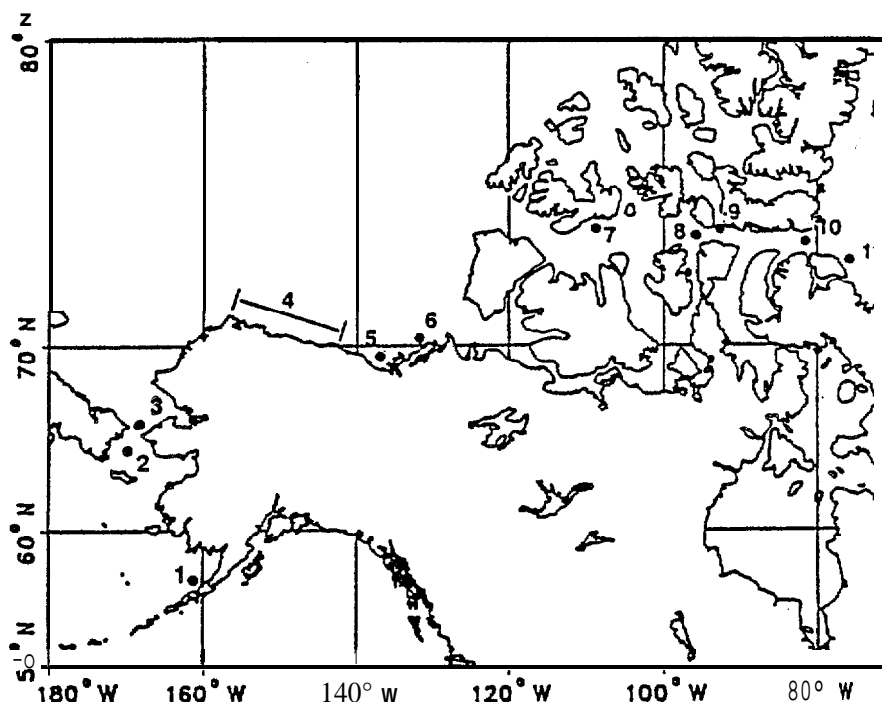


FIGURE 142. Collection sites for zooplankton samples whose isotopic content was analyzed during this project. (1) North Aleutian Shelf; (2) Northern Bering Sea; (3) Bering Strait; (4) Alaskan Beaufort Sea; (5) Mackenzie Bay, off Yukon coast; (6) Mackenzie Delta and Tuktoyaktuk Peninsula, eastern Beaufort Sea; (7) Bridport Inlet; (8) Resolute Passage; (9) Wellington Channel; (10) Lancaster Sound; and (11) Baffin Bay.

- 4a. Offshore Alaskan Beaufort Sea, Barrow to Canadian border: Samples were collected, sorted and frozen by D.H. Thomson of LGL and us on USCGS 'Polar Star', Oct 1986 (Fig. 143); sampling depths were <250 m over water depths 41-2070 m. For sampling details, see Table 7 in 'Zooplankton and Hydroacoustics' section (p. 151).
- 4b. Shelf waters of the Eastern Alaskan Beaufort Sea: Samples were collected by LGL personnel from the M/V 'Annika Marie', Sept 1985-86, and frozen in unsorted condition. Sampling depths were mainly <50 m over water depths <200 m (see Fig. 69 in 'Zooplankton and Hydroacoustics' section, p. 141).
- 5-6. Canadian Beaufort Sea: Samples were collected and frozen by LGL personnel in Mackenzie Bay '(1985-86) and off the Mackenzie 'Delta and Tuktoyaktuk Peninsula (1986) as part of a Canadian study on food availability to bowhead whales (Bradstreet and Fissel 1986; Bradstreet et al. 1987). The 1985 samples were frozen unsorted; the 1986 samples were sorted before freezing.
- 7-11. Central and Eastern Arctic: Archived formalin-preserved samples collected during 1976-78 in the Canadian Arctic Archipelago, Lancaster Sound and Baffin Bay" were provided by Denis Thomson of LGL .

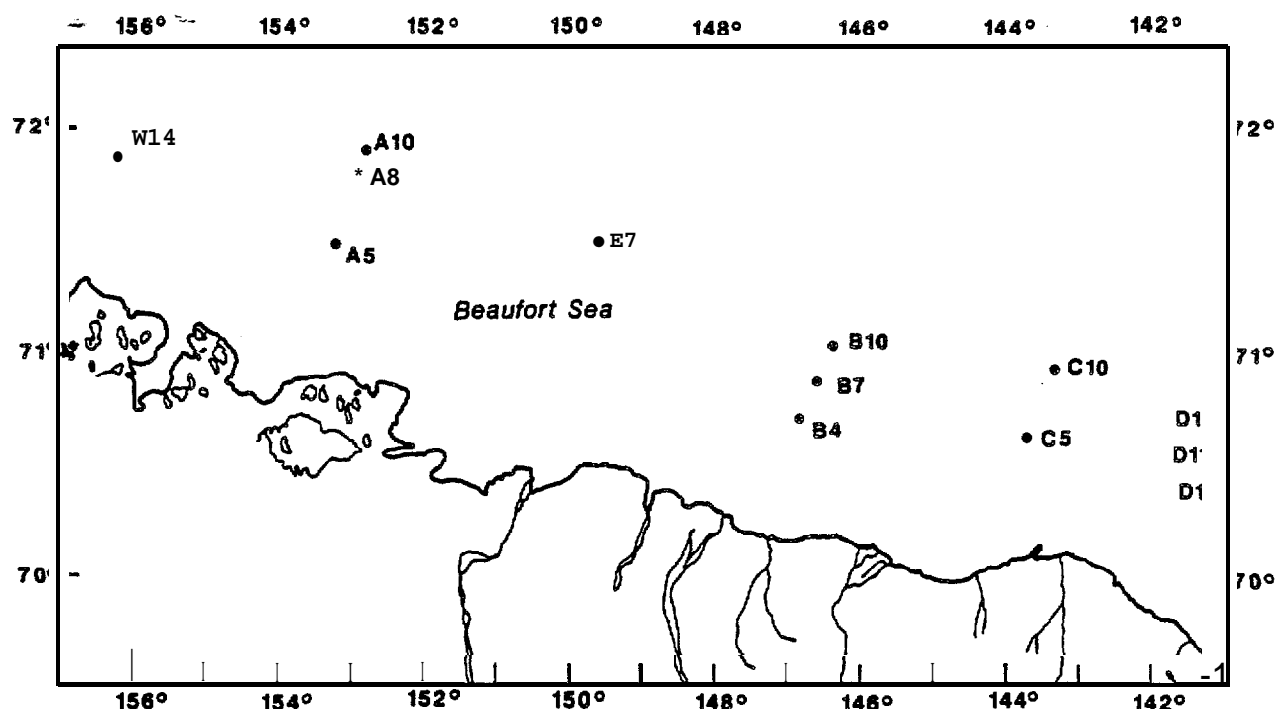


FIGURE 143. Zooplankton collection stations occupied in the Alaskan Beaufort Sea during USCGS 'Polar Star' cruise, October 1986.

The samples from the Bering, Chukchi and Beaufort Seas were collected either with bongo nets towed obliquely or horizontally, or (in ice-covered waters) with ring nets hauled vertically. In the collections where immediate sorting was not feasible, whole samples were frozen and then thawed and sorted at a later date in the laboratory. Samples handled in this latter manner were collections 4b (1985-86) and 5 (1985 only).

In addition, previously-available data on isotopic composition of zooplankton samples from the Alaskan Beaufort Sea (Dunton 1985) and Bering Sea (McConnaughey and McRoy 1979) were also considered.

Nutrient Samples. --Water samples were collected along boat transects 1985-2 and 1986-3 in the Eastern Alaskan Beaufort Sea. Sampling locations and details of sample preservation are given in the 'Zooplankton and Hydroacoustics' section (p. 160; Fig. 69 on p. 141). Nutrient samples were analyzed for nitrate, phosphate and silicate at the University of Alaska on a Technicon Autoanalyzer system. The results were contoured against depth and distance from shore to look for evidence of upwelling of nutrient-rich deep waters.

Bowhead Whale Tissues. --Arrangements were made with the North Slope Borough's Dept of Wildlife Management to acquire tissue samples from bowhead whales taken in the autumn of 1985 or the spring and autumn of 1986. In 1985 we requested blubber and muscle samples. In 1986 we requested visceral fat, muscle and baleen samples. No whales were taken at Kaktovik in 1985, but blubber samples from single bowheads taken at Barrow in the spring and autumn of 1985 were received. In 1986, both the spring and fall hunts for bowheads

were successful, and we obtained well-documented samples from 12 whales. We have more confidence in the analytical results from the well-documented 1986 samples than from opportunistically collected pre-1986 specimens.

### Stable Isotope Analyses

**Bowhead Baleen Samples.** --Baleen plates were excised from the jaws to include the most recently formed tissue and were carefully cleaned. The entire **plate** was scrubbed lightly with steel **wool** to remove the surface **film** of algae, etc. A strip of adhesive tape was **placed along** the **length** of the **plate** and marked off at 2.5 cm intervals from the base to tip. The **plate** was then sampled with a high-speed flexible shaft engraving tool **along** the **'outside' (unfrayed)** edge. After several milligrams of material was cut off, the fine shavings were collected on a piece of paper and placed in a **vial**. Approximately 14 **mg** of baleen was mixed with 750-1000 mg copper oxide and **placed** in a dental amalgam mixer and ground for **15-30 s**. This produced a finely incorporated mix of CUO and baleen. The mix was then poured into a short **length** of 6 mm quartz tubing **that** had been sealed at one end. This tube was then placed inside an outer quartz tube (9 mm x 220 mm) and allowed to dry overnight in a **100°C** oven. The tube was then evacuated on a high vacuum manifold to a residual pressure of less than 5 **millitorr** and sealed with a propane-oxygen torch. .

The tubes of samples were then **combusted** in a muffle furnace at **870°C** for 30 min and allowed to cool **to 700°C** over the course of several hours. The oven was then opened and the tubes removed when cool enough to handle. At this point **all C,N,H** and S was present in the tube as **CO<sub>2</sub>**, **N<sub>2</sub>**, **H<sub>2</sub>O** and **CuSO<sub>4</sub>**. The tube was then placed in a tube cracker (Des **Marais** and Hayes 1976) on the manifold and again evacuated to less than 5 **millitorr**. **After** isolating the manifold from the high vacuum, the tube was broken and the nitrogen, carbon dioxide and water vapor allowed to expand into the vacuum system, which contained a cold finger cooled with **liquid** nitrogen. First the nitrogen **was** collected by **Toeppler** pumping it into a short length of 6 mm tubing and sealing it off with a torch. The residual nitrogen was then pumped off and the **cold** finger warmed to **-50°C**. At this point the **CO<sub>2</sub>** vaporized and was collected in a tube cooled with liquid nitrogen. This tube was then sealed off with a torch for later analysis.

Tubes containing either N<sub>2</sub> or C<sub>2</sub> were loaded into the 20 sample automated **inlet** system on a **VG Isogas SIRA-9** isotope ratio mass spectrometer. Carbon (or nitrogen) isotope ratios were determined on six runs and the mean reported. **Results** are expressed in the conventional **'del'** notation, which represents parts per thousand deviation from the isotopic ratio in a standard:

$$\text{del value} = 1000 \times \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}}$$

where R is the absolute isotopic ratio. Our reference **CO<sub>2</sub>** standard was gas prepared by **Gollub, Inc.**, referred against PDB limestone. Our nitrogen standards were cylinder nitrogen gas and yeast powder referenced against air.



Bowhead Muscle and Fat Samples.--Muscle tissue was carefully trimmed while frozen to exclude surface layers of whale oil contaminant and then dried at 100°C to constant weight. Subsamples of 15 mg were then ground and treated as above.

Visceral fat was rendered by heating overnight after which time 12 mg of oil was placed by micropipette onto a small piece of glass fiber filter paper. The sample and filter paper were then ground with CuO and treated as above. Only CO<sub>2</sub> was isolated from oil due to the very small N<sub>2</sub> content.

Zooplankton Samples.--Most zooplankton samples used for isotope analyses, including all those from the Bering, Chukchi and Beaufort Seas, had been frozen or dried in the field. Formalin-preserved zooplankton samples were also analyzed to determine stable isotope ratios in areas adjacent to the study region. Preserved samples contained an unknown amount of formalin even after soaking in acidified distilled water for 24 h, but Dunton (1985) and Mullin et al. (1984) have shown that contamination is low and useful data can be obtained if samples are treated uniformly.

Zooplankters were rinsed lightly with distilled water and treated with 1N HCl to remove carbonates. Preserved samples were further soaked for 24 h to remove as much formalin as possible. Samples were then dried at 90°C. Subsamples of 10-15 mg were ground with CuO, combusted as described above, and analyzed by mass spectroscopy,

#### Validation of Methods for Baleen Analyses

Internal Checks for Uniformity in Baleen Growth.--Consistency in stable isotope abundances within a given transverse section of baleen plate was tested on baleen from whale 86WW2, a very large animal taken at Wainwright. At a point 52 cm from the base, small samples of baleen were taken across the plate at approximately 2.5 cm intervals. These were then run for carbon and nitrogen isotope ratios as described above.

To test the premise that isotopic abundances are similar at corresponding positions along all plates, two plates--one from each side of the mouth--were collected from whale 86KK1. These plates were aligned side by side and samples taken from equivalent locations along each plate. Since the two plates were of nearly the same length and the transverse ridges aided visual matching of locations, the paired samples were probably deposited at very close to the same time. The matched samples were analyzed for nitrogen and carbon isotopes.

Determine Periodicity of Stable Isotope Oscillations.--Figure 141 shows the variations in the C-13 content of a 3.2 m piece of baleen from a large adult whale harvested in 1971. Peaks average 18.8 cm apart and are remarkably regular over the length of the baleen plate. The marked oscillations are believed to occur in response to variations in the stable isotope content of zooplankton consumed as the whale moves through different feeding areas (see Results, below). The peaks in the baleen record could conceivably have arisen from three sources: (1) annual migration from the Bering Sea to Beaufort Sea and back, (2) one or more intraseasonal movements from an area of the Beaufort Sea with zooplankton depleted of C-13 to an area with prey more enriched in C-13, or (3) shifts in diet at a given location between prey species of differing isotopic composition. With regard to point (3), copepods are

depleted in C-13 relative to mysids *and euphausiids* (see Results, **below**) and all of these animals are preyed upon by bowheads (Lowry and Frost 1984). A possible complication is that baleen **laid** down during periods of partial or total fasting might incorporate internally mobilized lipids and protein acquired from food consumed in other regions and seasons. In any case, it was important to determine if the observed peaks were annual or represented some other time interval.

The period of the stable isotope cycles can be determined by measuring C-14 (radiocarbon) content at various points **along** the baleen. The large whale harvested in **1971** (Fig. 141) lived through the **1960's**, when the USSR and the USA conducted much nuclear weapons testing in **the** atmosphere (especially during 1960-63). Total input of C-14 **to** the atmosphere was **an** estimated  $7 \times 10^{23}$  atoms from 1954 to **1963**, when the Partial Test Ban Treaty was signed. This C-14 was enough to almost double the atmospheric content in the northern hemisphere (Nydal et al. 1980), and **to** provide a unique time-mark at 1963-64. Prior to 1954, the only change in **C-14** other than natural decay was a **small** dilution of atmospheric carbon dioxide by **inputs** of  $\text{CO}_2$  from burning of fossil fuel. Since the lifespan of a whale is too short to record measurable **radiodecay** of **C-14** (half-life = 5570 years), any changes in radiocarbon **along** the baleen must arise from external factors.

Radiocarbon concentrations in surface ocean water of the Bering Sea and Arctic Ocean, and in the organisms living therein, were about **90-95%** of C-14 concentrations in the overlying atmosphere prior to 1954 (Broecker et al. 1980)". By convention, the C-14 activity in the atmosphere in 1950 is defined as 'normal background' or 'modern' and equals 100 percent. The 5-10% reduction **in** C-14 abundance in marine water is due to the delay in equilibrating the atmospheric  $\text{CO}_2$  with the chronologically older  $\text{CO}_2$  brought to the ocean surface following deep mixing and **upwelling** events in the water column. Since **primary** productivity is usually enhanced by nutrients that are brought Up to surface waters by these same mixing **events**, radiocarbon depressions are often **'built 'in'** to oceanic food chains since the carbon, once fixed by plants, is no longer capable of exchanging with the atmosphere. This process is most pronounced in highly productive waters of **upwelling areas** and the deep-mixed waters of **subpolar** regions. The resulting radiocarbon activity in the **biota** of northern waters prior to 1954 was therefore about 90% modern. If there had been no **anthropogenic** additions to the atmosphere, the radiocarbon content of the **biota** would have varied only within the narrow range induced by the normal year to year differences in oceanic mixing.

In the **years** 1960-63, the intensive **weapons** testing irreversibly altered the radiocarbon regime of the earth for many thousands of years to come. The radiocarbon released to the atmosphere was dispersed by atmospheric circulation within a few months in **the** northern hemisphere and within a year throughout the world (Fig. 144; Broecker et al. 1978). Of approximately 511 MT of atmospheric explosions prior to the **1963** Treaty, about 294 MT were between **fall** 1962 and August **1983**. Atmospheric C-14 concentrations increased from **near** 40% above background to **>102%** during this period (Nydal et al. 1980). Large quantities of nuclear explosion products were received promptly in Alaska. As this radiocarbon transferred to the surface of the ocean, the radioactivity in the **biota** underwent a corresponding increase. The rate of increase in the arctic marine system was not measured, but Figure 145 illustrates modeled increases in radiocarbon in the north temperate Atlantic

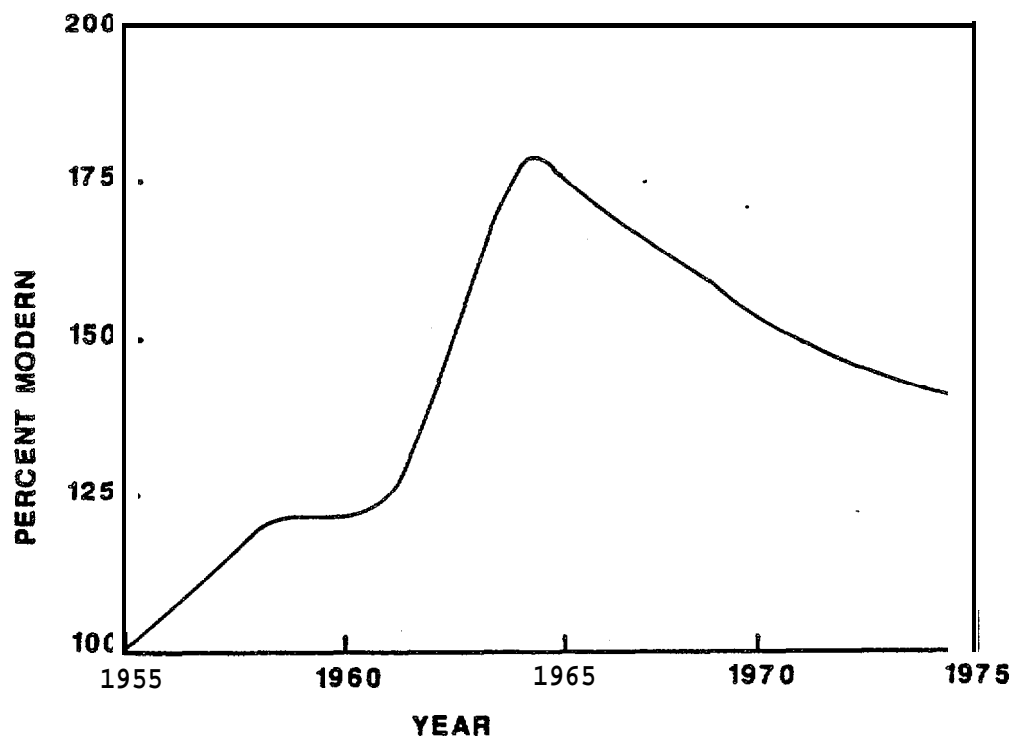


FIGURE 144. Radiocarbon (C-14) activity in the atmosphere at 45°N, 1955-75. Modified from Broecker et al. (1980).

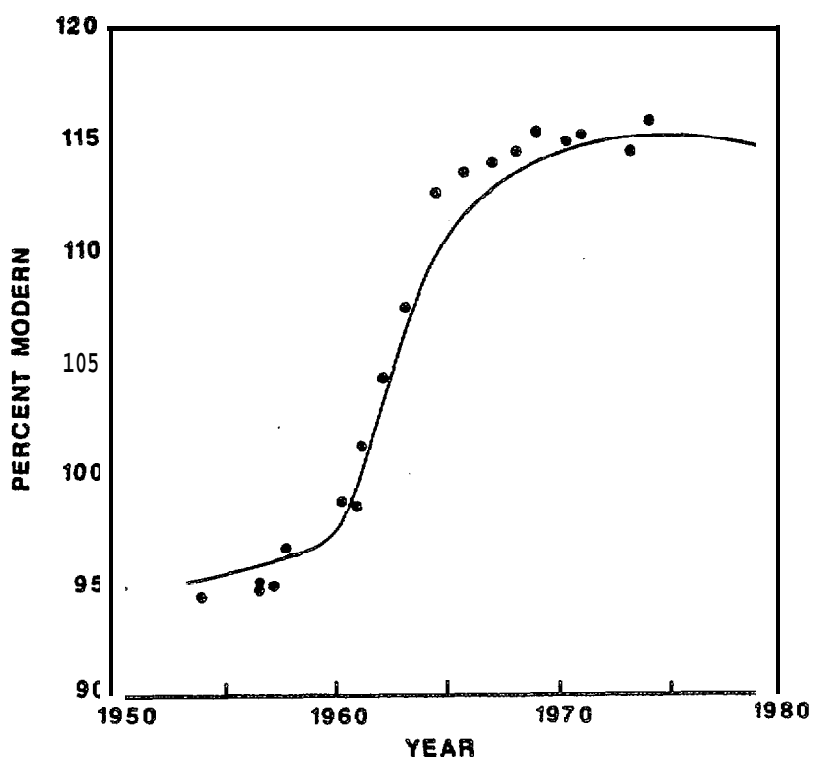


FIGURE 145. Predicted radiocarbon (C-14) activity in surface seawater (solid line, from Broecker et al. 1980) and measured values in known-age growth-rings of corals from Florida (from Druffel and Linnick 1978).

(Broecker et al. 1980) along with C-14 data from known-age growth-rings in coral from Florida (Druffel and Linnick 1978). The good fit indicates that the C02 invasion rates calculated for the temperate ocean are quite realistic. Similar invasion curves can be expected for higher latitudes but with lesser amounts of radiocarbon being evident, due to the more effective dilution by deeper mixing during winter months. Broecker et al. (1980) noted that in 1973 the surface water of the Arctic Ocean was at 105% modern. This agrees very well with the observed value of 105.7% modern in kelp from the Alaskan Beaufort Sea in 1979 (Schell 1983).

To test if the observed oscillations in the C-13 content of the baleen from whale 71B were annual, nine 10-gram pieces of baleen were cut at points along the plate and analyzed for radiocarbon content. Samples were analyzed by Beta Analytic of Coral Gables, Florida, a commercial laboratory specializing in this service. Radiocarbon activities at various points along the baleen plate were then compared with the predicted values, assuming an annual cycle of C-13 content, to see if the temporal agreement was correct for an annual cyclicity in the C-13 peaks.

For further verification, a second piece of baleen was also analyzed for stable isotope abundances and radiocarbon activity. This specimen, collected at Barrow in 1966 by Floyd Durham for the Los Angeles County Museum, was supplied by Dr. John Heyning, Curator. Small samples were clipped at 2.5 cm intervals for stable isotope analysis, and 10 g pieces for C-14 analyses were cut 5, 22, 55, 80, 105, 132 and 165 cm from the base end.

## Results and Discussion

### Stable Isotope Ratios in Zooplankton

Geographic Gradients.--The extensive zooplankton collections made in 1985-86 were analyzed for stable isotope abundances during this study, and compared with previous findings (cf. Dunton 1985). The depletions in C-13 that were observed in the eastern Beaufort Sea in past years have been confirmed, and a more complete record of carbon isotope abundances in prey is now available for various parts of the range of Western Arctic bowhead whales. The areas from which data are still absent or scarce are the northern and western Bering Sea (the wintering grounds), the Chukchi Sea, far offshore parts of the Canadian Beaufort Sea, and Amundsen Gulf.

In 1985, we analyzed the C-13 content of copepods, chaetognaths and other organisms from the Eastern Alaskan Beaufort Sea and Mackenzie Bay areas, both of which were farther east than the parts of the Alaskan Beaufort Sea where Dunton (1985) had worked. The 1985 results showed that the trend for decreasing C-13 content from west to east noted by Dunton continued east at least as far as Mackenzie Bay (138°W; Fig. 146).

In 1986, additional samples were obtained across the Alaskan and Canadian Beaufort Sea, along with very limited samples from the northern Bering Sea (Fig. 147). In the official study area, euphausiids collected in September and October 1986 show a C-13 depletion relative to the euphausiids collected farther west in the Alaskan Beaufort and Bering Seas (Fig. 147; Table 54). Similarly, the copepods collected in the study area in 1986 were

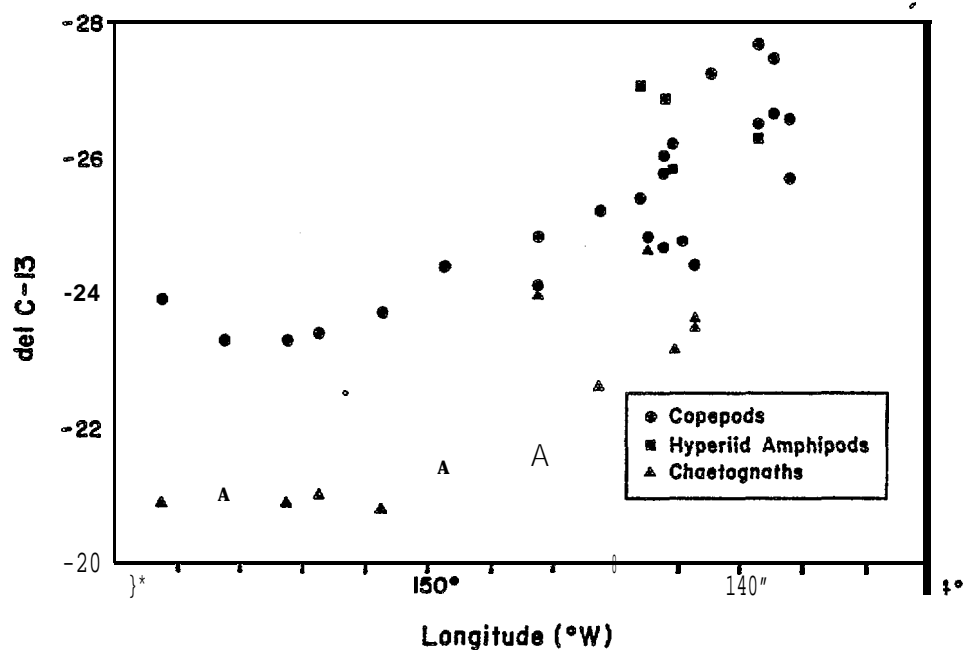


Table 54. Carbon isotope ratios ( $\delta$  C-13) of euphausiids and copepods, 1985-86.

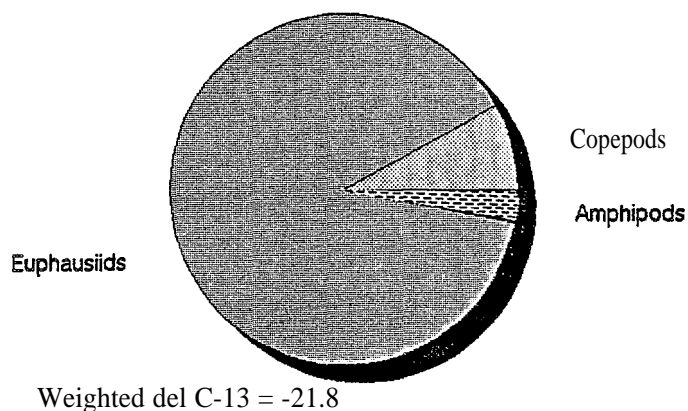
Area	Year	Copepods			Euphausiids		
		Mean	s.d.	n	Mean	s.d.	n
N. Bering	1986	-23.9		1	-19.9	-	1
W. Alaskan Beaufort Sea	1986	-22.8	0.9	5	-21.7	0.8	15
Central Alaskan Beaufort Sea	1986	-24.6	0.6	4	-23.5	0.4	8
E. Alaskan, Beaufort Sea, (Study Area)	1985	-25.8	0.8	7	-21.6	-	2
	1986	-26.2	1.3	34	-24.7	1.3	9
W. Canadian Beaufort Sea <sup>a</sup>	1985	-26.7	0.7	6	-24.0	0.2	3
	1986	-25.1	1.0	6	-23.3	-	2

<sup>a</sup> Samples collected by Bradstreet and Fissel (1986) and Bradstreet et al. (1987).

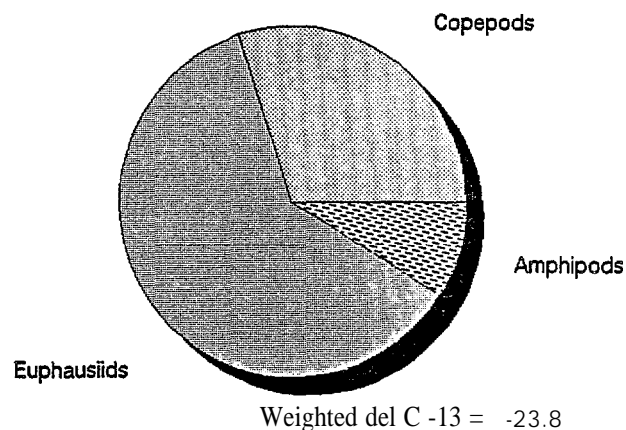
isotonically lighter than those collected farther west (Fig. 147). The C-13 depletion of the major prey species of the Eastern Alaskan Beaufort relative to zooplankton farther west is shown more dramatically when relative biomasses of the various organisms in different areas are considered. Copepods contributed a much larger proportion of the biomass in the eastern than in the western Alaskan Beaufort Sea. An opposite trend was evident for euphausiids (Fig. 148). Weighted mean  $\delta$  C-13 values were calculated for the Western, Central, and Eastern Alaskan Beaufort Sea based on the relative biomasses of the major prey groups--copepods, euphausiids, amphipods, mysids (Fig. 148). Hydrozoans, ctenophores, and other soft-bodied organisms were not included in the calculations. Their biomasses, although sometimes large, are mostly water and the carbon equivalent is small.

Because of the shift from predominantly copepods (less C-13) in the east to predominantly euphausiids (more C-13) in the west, there was, in the available prey, a very marked trend for increasing C-13 content from east to west across the Alaskan Beaufort Sea. There was a 4 ppt geographic difference in zooplankton as a whole as compared to the 1-3 ppt difference seen in copepods or euphausiids separately (Fig. 149). Although zooplankton biomass data are not available from the western and central parts of the Alaskan Beaufort Sea in 1985, the weighted  $\delta$  C-13 for Eastern Alaskan zooplankton in 1985 was almost identical to the 1986 value (Fig. 148D vs. C).

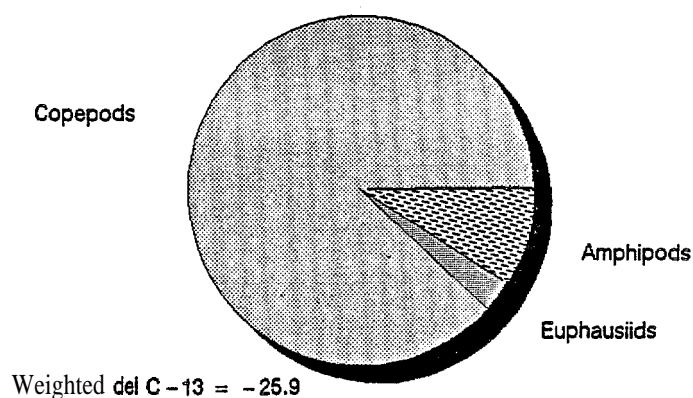
A. Major Prey Fractions - Western, 1986



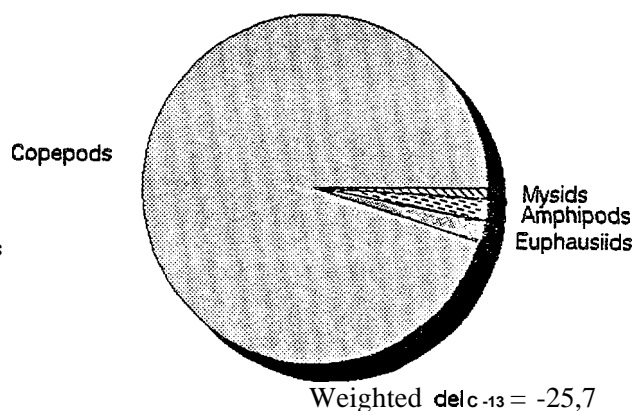
B. Major Prey Fractions - Central, 1986



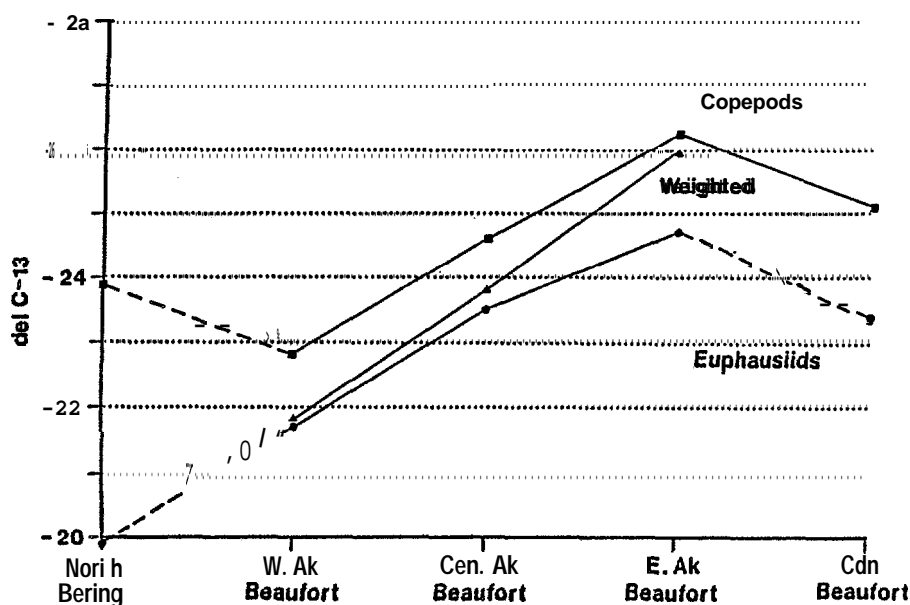
C. Major Prey Fractions - Eastern, 1986



D. Major Prey Fractions - Eastern, 1985



**FIGURE 148.** Proportional biomass of major bowhead whale prey types in various parts of the Alaskan Beaufort Sea, and weighted mean  $\delta C-13$  content in each area. A and B show October data; C shows pooled Sept-Oct data (values for the two months were similar); D shows Sept data.



**FIGURE 149.** Mean C-13/C-12 ratios in **copepods** and **euphausiids** across the Beaufort Sea in 1986, and the weighted average ratio in the food available to bowhead whales migrating through the Alaskan Beaufort Sea.

General geographic trends were similar in 1985 and 1986, and consistent with the earlier data of Dunton (1985). The maximum depletions in C-13 were found in **zooplankton** from the eastern Alaskan and Canadian parts of the Beaufort Sea, the summer feeding grounds of bowhead whales. These depletions may decrease farther east in the Canadian Arctic Archipelago and Baffin Bay (sites 7-11 in Fig. 142). However, our data from those areas came from **zooplankton** samples preserved in **formalin** and stored for several years, and may be unreliable. Hence, we chose not to present the data from **formalin**-preserved samples.

Geographic vs. Taxonomic Differences in Isotopic Content.--There is a difference of 2 ppt or more in the C-13 content of copepods in the eastern and central Beaufort Sea (summering area of bowheads) vs. the western and southern parts of their range (Fig. 149 and Table 54). If bowhead whales fed solely upon **copepods** and fed in late fall and winter as well as summer, a shift of 2 ppt would be expected in the C-13 content of their tissues over the annual cycle, assuming a complete replacement of body carbon in six months.

The C-13 content of different types of **zooplankton** collected at the same locations and times differs. We have emphasized data on the isotopic content of **copepods** and **euphausiids** because these are major prey items of bowheads. At most locations, euphausiids contained 1-3 ppt more C-13 than copepods (e.g. Fig. 147). Similarly, **chaetognaths** contained more C-13 than copepods (Fig. 146). Euphausiids and **chaetognaths** probably had more C-13 than did copepods because the former two types of animals are omnivores or predators whereas **copepods** are herbivores. Predators generally contain a higher proportion of C-13 than their prey (McConnaughey and McRoy 1979; Fry et al. 1984). Differences in lipid content may also be a factor, since lipid tends to be depleted of C-13 (McConnaughey and McRoy 1979; Tieszen et al. 1983). Copepods have higher lipid content than other major **zooplankton** groups in the Beaufort Sea (Bradstreet et al. 1987).



Limited stomach content **data** from whales harvested near Point Barrow in **autumn** are consistent with the hypothesis **that bowheads** more commonly feed on euphausiids in the Point Barrow area than farther east in the Beaufort Sea (Lowry and Frost 1984). At **least** in October 1986, euphausiids were more common in the western than the eastern **part** of the Alaskan Beaufort Sea (Fig. 80 on p. 184, Fig. 148). If this is also true at other locations in the western part of the range (e.g. near Herold shoal off the USSR), and if the **bowhead** diet reflects available **zooplankton**, the combined effects of the geographic and herbivore-predator differences in **C-13** could result in a **large** change in the **C-13** content of the whale's diet **as it travelled** west--much larger than the 2 ppt associated with the geographic trend **alone** (Fig. 149). This may be the explanation for the oscillations of >3 ppt in the **C-13** content of some **baleen plates** (see below).

At present, we have few data on isotopic content of **zooplankton** from the northern Bering Sea and **Chukchi** Sea, where bowheads occur in late **autumn**, winter and **early** spring. It is uncertain whether isotopic content there differs from **that in** the western part of the Alaskan Beaufort Sea. We **also** have no winter samples--important consideration given the seasonal variations in lipid content of **copepods**, and the differences in isotopic content of **lipids** vs. **other** components. Continued sampling of zooplankton to measure its **taxonomic** composition, biomass and isotopic abundances may resolve these points, and **also** allow discrimination between geographical and environmental effects. During the spring of 1987, samples of numerous **zooplankton species** were collected in the northwestern Bering Sea. We will be collecting in the southern **Chukchi** Sea-Bering Strait region in **fall** 1987 and in the northwestern Bering in early winter 1987. Analysis of **these** samples will provide data on the isotopic composition of potential prey organisms in the southwestern part of the range of bowhead whales.

#### Stable Isotope Ratios in Bowhead Baleen

Preliminary analyses showed that the **C-13/C-12** ratio oscillated in a remarkably regular fashion at intervals of **about 20 cm** **along** the length of **baleen plates** (Fig. 141). The **baleen** grows progressively from the upper jaw, and is inert once laid down. Hence, the isotopic ratio at each point along the **baleen** presumably reflects the isotopic composition of the energy source (food or reserve tissue) at the time of formation of **that** baleen, with a **small C-13** enrichment resulting from metabolic processes. Tieszen et al. (1983) have shown that- keratin in lab animals is enriched in C-13 by approximately four ppt relative to lipid and one ppt relative to the muscle tissue. However, to use **the stable** isotope ratios in bowhead **baleen** as a reliable indicator of the food consumed **at various places** and times, it is first necessary to establish the pattern of variation in isotope content within and **between baleen** plates.

**Variations Across Single Baleen Plates.--****Baleen** growth in the **jaw** does not occur at a flat site at **the end of** the baleen. Instead the base of the **plate** has a narrow pocket filled with **tissue** from which the **cells** are laid down to harden into baleen. In a large whale this pocket may be >3-4 cm deep in the center. Thus, the **baleen** in a given cross-section of a baleen plate could be deposited over 2-3 months if grown at an overall rate of 20 cm/yr. To reduce this source of possible variability, we limited sampling to the surface layers, preferably along the outside edge of the **baleen plate**.

To test the **variability** in C-13 content across the width of a baleen plate, we sampled a large **plate** from whale 86WW2 at 2-3 cm intervals across its 25+ cm width. The results display good consistency (Fig. 150). Our **overall** analytical precision for c-13/C-12 ratios, including the entire process of sampling, combustion, cleaning, and mass **spectrometry**, is typically about  $\pm 0.2$  ppt. Within this range of uncertainty, **the** isotopic abundances in portions of a baleen plate laid down at a given time are constant.

The isotopic ratios for nitrogen were also consistent across the width of the **plate** (Fig. 150). The **slightly** greater range of variation than for carbon isotopes was consistent with the slightly lower analytical precision ( $\pm 0.3$  ppt) of the nitrogen analyses.

Variations Between Plates from One Whale. --To test whether **all** plates in the mouth of a whale receive identical **isotopic** abundances at a given **time**, two **plates** from opposing **sides** of the mouth were collected from whale 86KK1. Matched samples from equivalent locations along 65 cm sections of the two plates were analyzed. Temporal alignment of the plates was possible because the plates, like those of other bowheads, had distinct patterns of transverse ridges that were similar in both plates. By matching the two plates and cutting the samples at equivalent locations, we hoped to acquire isotopic abundance data on baleen laid down at the same **time**.

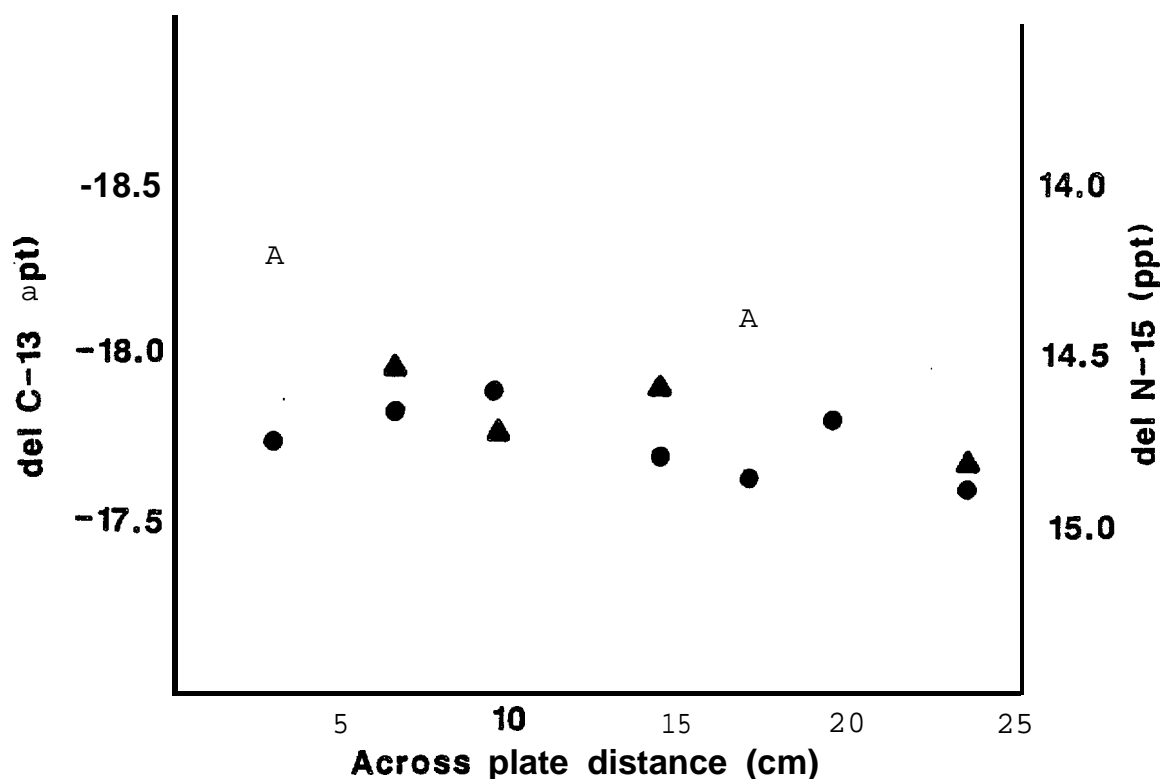


FIGURE 150. Carbon (circles) and nitrogen (triangles) isotope ratios across a baleen plate from bowhead 86WW2, taken at Wainwright in spring 1986. Total width of the **plate** was 25 cm.

The results indicate that two plates from one whale contain consistent patterns of carbon and nitrogen isotopes (Fig. 151). The minor differences between the two plates probably resulted from slight differences in the relative locations of sampling in regions of the baleen where isotopic ratios were changing rapidly. In any case, the data validate the premise that the isotopic record from any of the longer baleen plates from a given whale will give a consistent record of the changes in isotope ratio in its past history.

Evidence that Isotopic Periodicity is Annual.--Figure 152 shows the stable isotope data from whale 71B plus the C-14 content at nine points along its length. As described in the Methods subsection (p. 378 ff), the rapid rise in radiocarbon content of the ocean surface occurred after 1963, the year when over half of the atmospheric nuclear weapons testing took place. In the late summer and autumn of 1963, during the period of maximum open water, Arctic Alaska received fallout from very large nuclear tests in Novaya Zemlya. Since the majority of the radiocarbon likely began infiltrating surface waters late in the summer and autumn of 1963, the marine biota probably were not severely impacted that year; most of the primary production for the year had already occurred. By the spring of 1964, however, a sizeable fraction of the carbon dioxide containing C-14 would have equilibrated with the ocean surface and was available for plant uptake in the spring bloom. By 1965, radiocarbon activity in surface water may have risen over half way to its final equilibrium concentration with the atmosphere (Fig. 145).

The radiocarbon concentrations along the plate from whale 71B are widely scattered, but show the rise in concentration over the time spanned by the growth of the plate. The samples were cut from specific points along the plate; each sample represents about 2.5-3 cm of length or about  $1\frac{1}{2}$  months of baleen growth if the C-13 oscillations were annual. This method of sampling tends to accentuate the normally high variability in the radiocarbon content in marine organisms. As an illustration of the normal variability in radiocarbon content, C-14 content of seven whales killed in the spring of 1986 varied by almost 5% (Fig. 153). This variability may be due to the large between- and within-year variations in the amount of upwelling to the euphotic zone. Upwelling brings chronologically old water to the surface, with an accompanying depression in C-14. The occurrence of upwelling in the Beaufort Sea is variable from year to year and place to place; for example, it occurred in the Eastern Alaskan Beaufort Sea in September 1985 but apparently not in September 1986 (Fig. 154).

Thus, the radiocarbon data from whale 71B reflect both the increases in C-14 incurred from assimilation of bomb radiocarbon and the depressions brought about from the intermittent deep mixing and upwelling events that are typical of the Bering and Beaufort Seas. Nevertheless, it would have been impossible for the whale to acquire a radiocarbon content in excess of the 1950 modern value of about 90% without major inputs of bomb C-14. The record suggests that this occurred about 9 del C-13 cycles before the death of the whale in 1971, i.e. during the early 1960s if the cycles are annual. However, the scatter in the C-14 data, most notably the elevated C-14 value occurring thirteen del C-13 cycles before death, left some doubt that the peaks are annual increments.

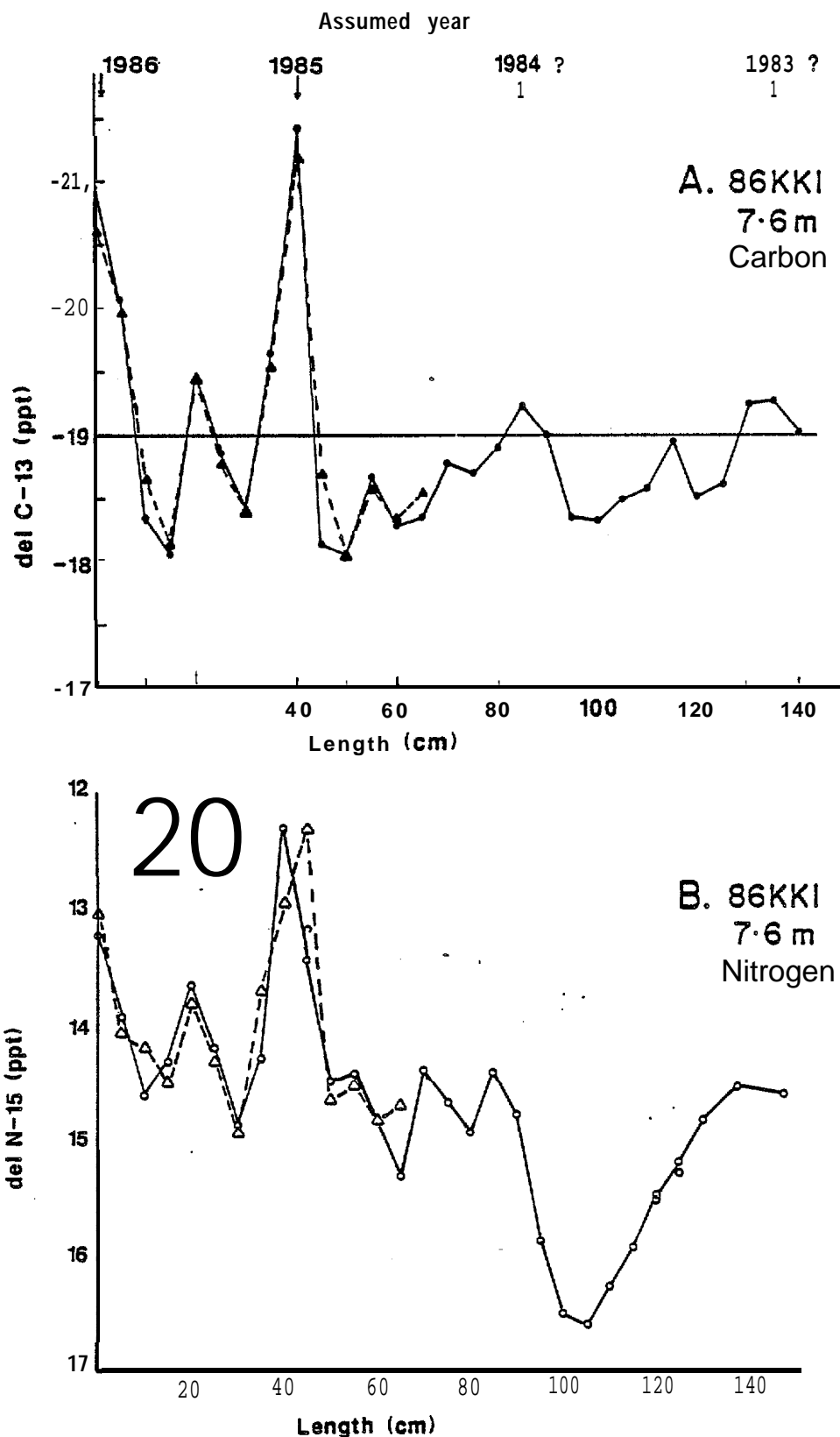


FIGURE 151. Carbon (A) and nitrogen (B) isotope ratios along two baleen plates from bowhead 86KK1, taken at Kaktovik in autumn 1986. Solid line shows data from full length of plate on left side of mouth; dashed line shows data for 65 cm of corresponding plate on right side. The year scale assumes that the c-13/C-12 oscillation is annual.

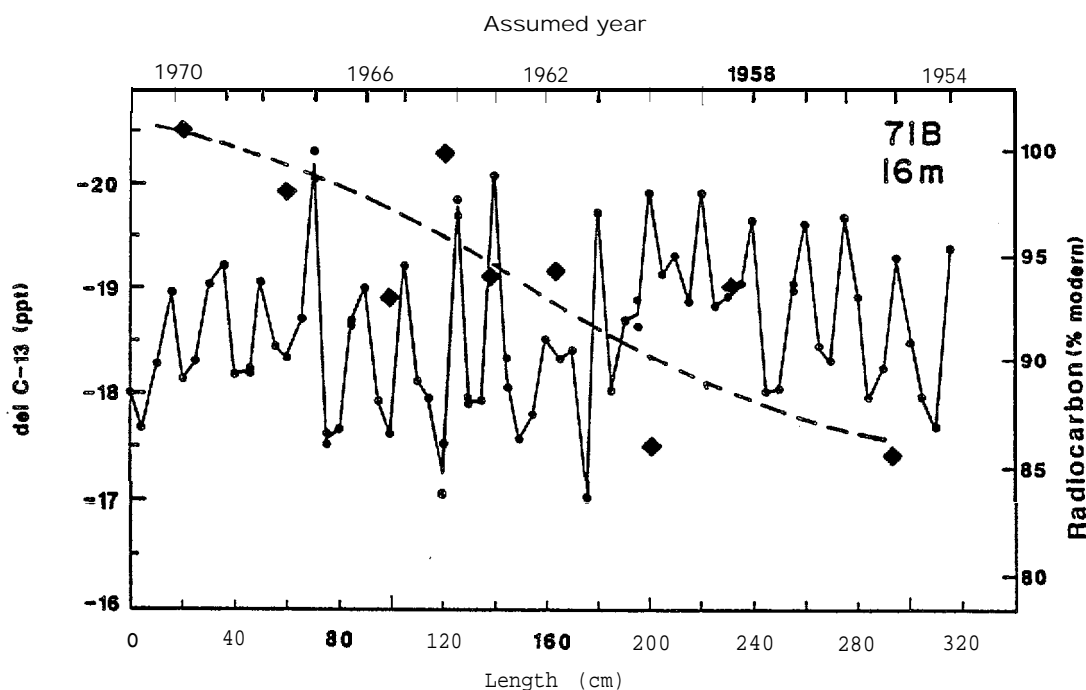


FIGURE 152. Carbon isotope values along baleen of bowhead 71B, a large whale taken at Barrow in 1971. Radiocarbon (C-14) activities are shown (diamonds) for 9 points along the baleen. The year scale assumes that the C-13/C-12 oscillation is annual. Dashed line is the approximate concentration of C-14 from nuclear weapons testing (after Roether et al. 1980), plotted against the year scale.

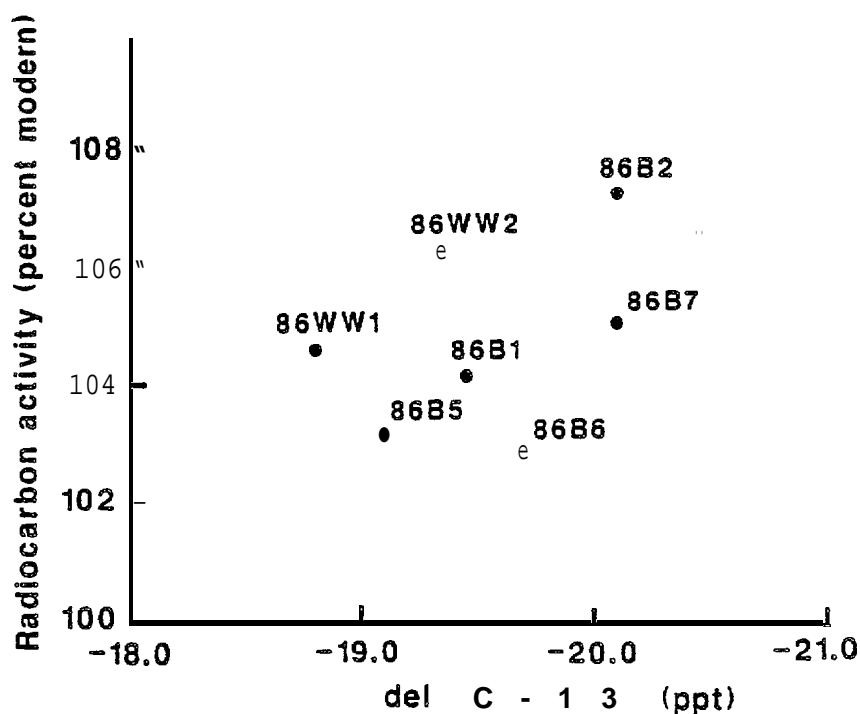


FIGURE 153. Radiocarbon (C-14) activities and C-13/C-12 isotope ratios in muscle tissue from bowheads taken in spring 1986.

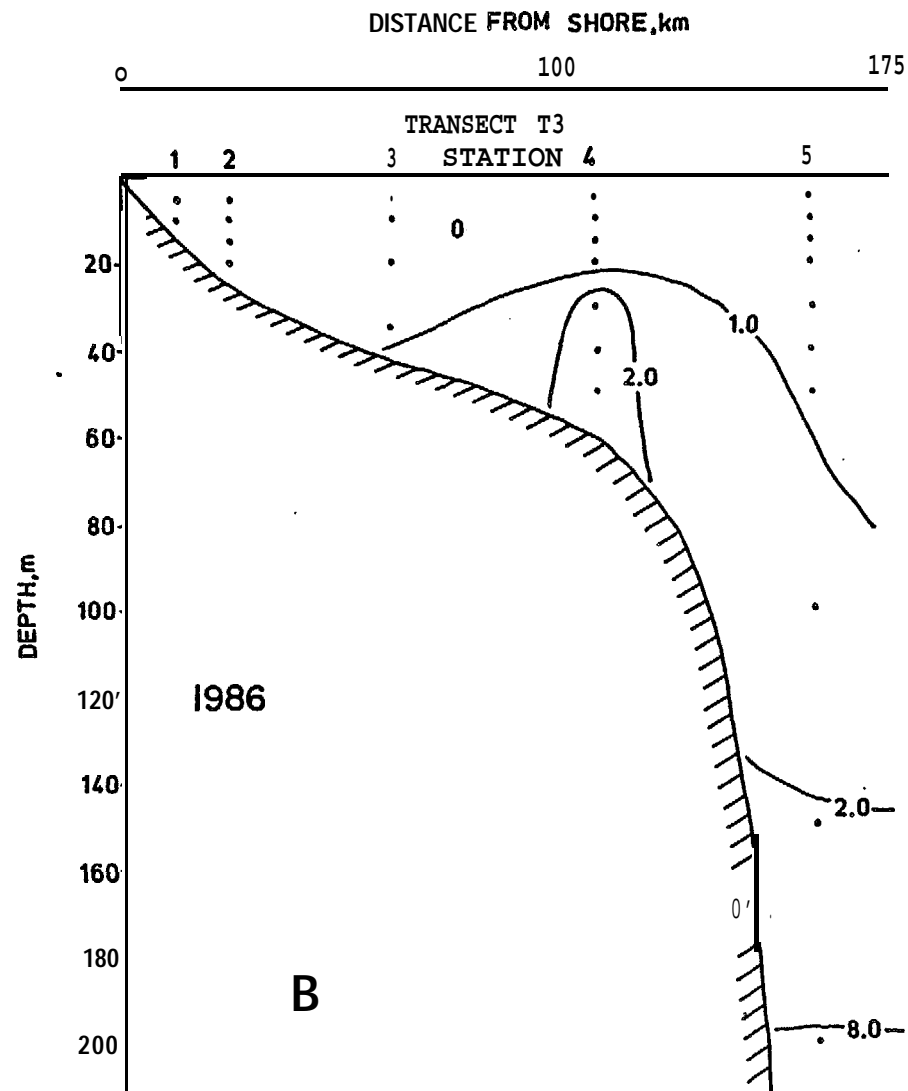
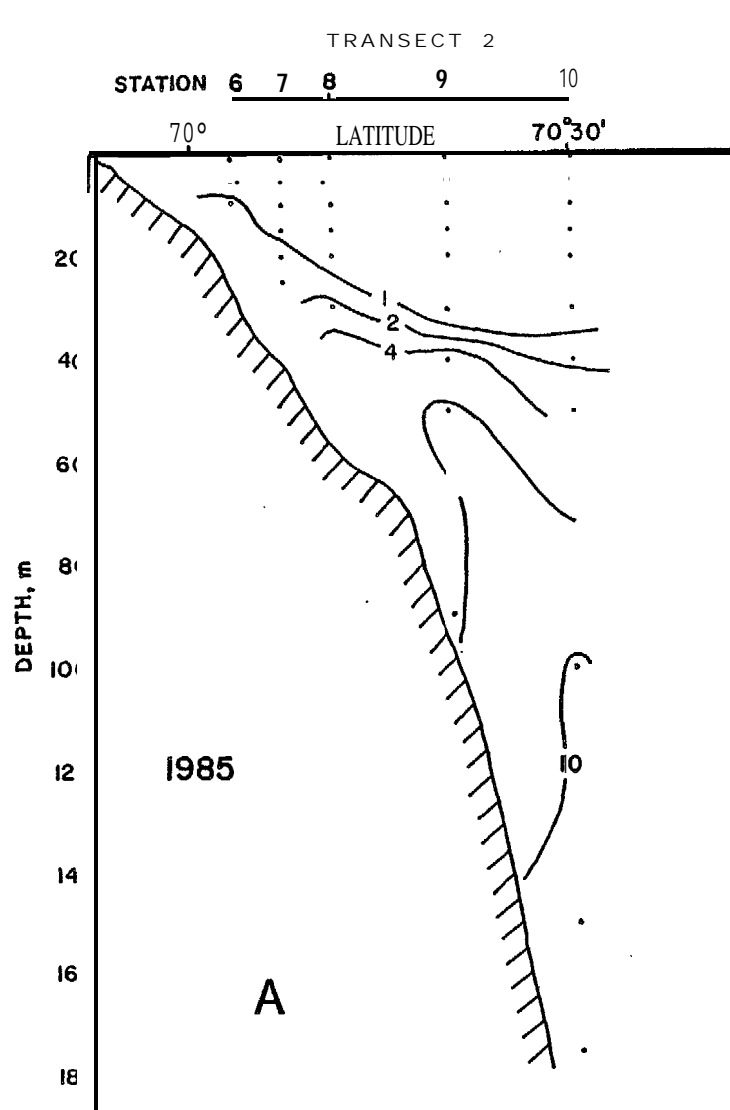


FIGURE 154. Nitrate concentrations (micromoles/L) along transects perpendicular to shore east of Kaktovik during September of 1985 and 1986. See Fig. 16, 44, 48 in 'Water Masses' section for transect locations and temperature/salinity cross sections. Note evidence of upwelling in 1985 but not 1986.

The scatter in the C-14 data from whale 71B led us to conduct a similar radiocarbon analysis of the baleen from whale 66B1, which was acquired from the Los Angeles County Museum. The samples for radiocarbon analysis were cut lengthwise along the baleen plate such that the 10 g pieces spanned 10-15 cm of the plate or an assumed interval of 4-7 months if each  $\delta$  C-13 cycle represents one year (cf.  $1\frac{1}{2}$  mo for whale 71B). This technique was chosen to smooth out short-term variability and produce an 'average' radiocarbon activity for the period in question (Fig. 155). The radiocarbon content averaged about 92% modern for the first five peaks of the seven-peak record, but then rose rapidly, reaching 106% modern by the end of the plate. This rapid rise in radiocarbon content after peak five is indicative of the assumed 1964 influx of bomb radiocarbon. Since the main radiocarbon influx probably occurred two years prior to the death of the whale in 1966, and two C-13 peaks are present after the rise in radiocarbon in the plate, the C-13 peaks appear to be annual.

Another important piece of evidence for the annual nature of the oscillations in C-13 content lies in the measured stable isotope ratios in the baleen that was being formed when the whales were killed (see left edges of subsequent diagrams). The most recently formed baleen in most ( $n = 6$ ) if not all ( $n = 8$ ) whales known to have been killed during spring was enriched in C-13, i.e. at a 'valley' in the oscillation as shown on our graphs. (The two questionable cases were 'ingutuks', see Fig. 159, later). These whales were coming from the Bering Sea, where the zooplankton is enriched in C-13. In contrast, the most recently formed baleen in all whales killed in autumn ( $n =$

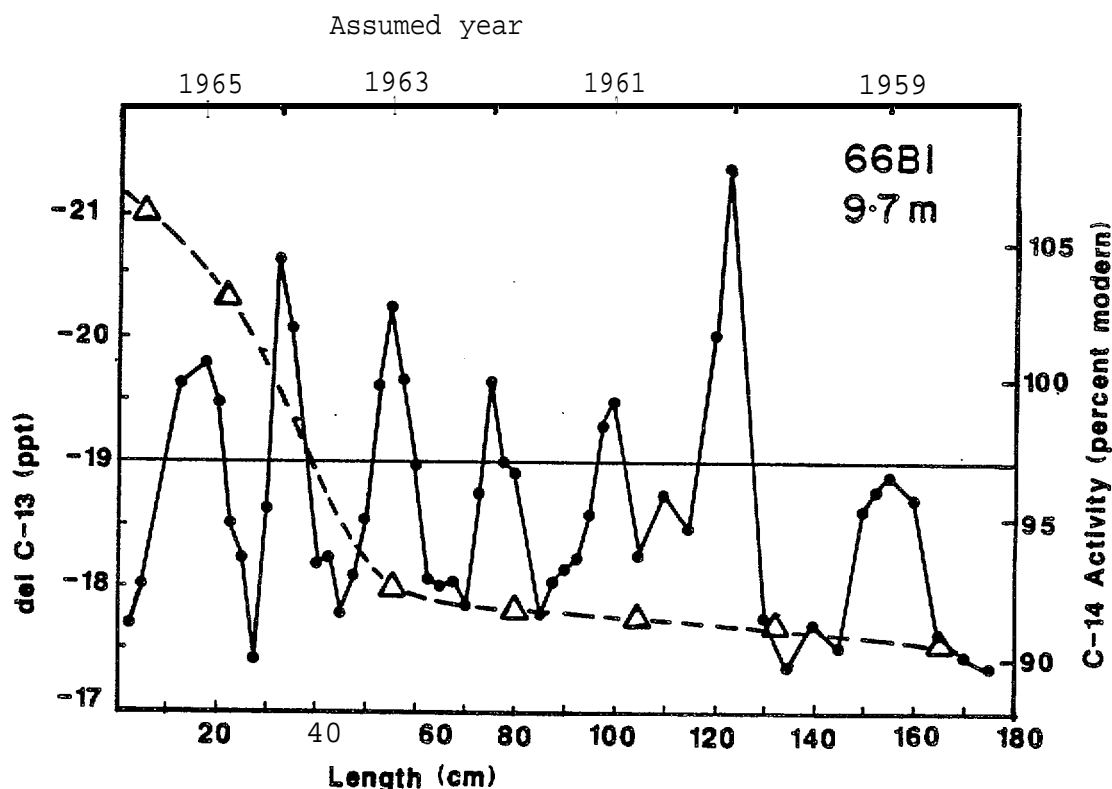


FIGURE 155. Radiocarbon activities (triangles) and carbon isotope ratios along baleen of bowhead 66B1, taken at Barrow in spring 1966. The year scale assumes that the C-13/C-12 oscillation is annual. Dashed line is fitted to the points.

3) was at or near a 'peak', i.e. depleted in C-13. These whales had just spent the summer in the eastern Beaufort Sea, where zooplankton is depleted of C-13. This is a strong indication of an annual cyclicity in the record. (Note: The baleen from whale 71B is undocumented except that the whale was killed at Barrow in 1971. The isotopic record [Fig. 152] indicates that it was taken in the spring.)

In summary, several types of data, singly and especially in combination, provide strong evidence that the observed oscillations in C-13/C-12 ratio along baleen plates are annual. This evidence consists of (1) the radiocarbon data, (2) the observed geographical gradients in the C-13 abundance in zooplankton along the annual migration route of the whales, and (3) the differences in C-13 values in the baleen formed just before whales were killed in spring vs. autumn.

Physical Characteristics of Baleen in Relation to Age.--Over 165 years ago, the British whaling captain William Scoresby stated that,

'In some [bowhead] whales, a curious hollow on one side, and ridge on the other, occurs in many of the central blades of whalebone, at regular intervals of 6 or 7 inches. May not this 'irregularity,' like the rings in the horns of the ox, which they resemble, afford an intimation of the age of the whale? If so, twice the number of running feet in the longest lamina of whalebone in the head of a whale not full grown, would represent its age in years.' (Scoresby 1820)

The baleen plates of bowhead whales appear at first glance to be smooth, narrow isosceles triangles with the characteristic hairs on one side and a posteriorly curved outside edge. The overall plate usually has a gentle curve depending upon its position in the row in the whale's mouth. It is also noticeable that the plate is actually made up of a myriad of transverse ridges analogous somewhat to the fine detail that runs lengthwise in a human fingernail. On most but not all plates, there are 'zones' of rougher textured baleen and sharp increases in width of the plate. These take the appearance of shallow steps. Durham (1978) described this sculpturing in the baleen; he noted that Scoresby was the first to assume annularity of the steps and that this belief continued up into the 1950s (Nishiwaki 1950). Ridges in rorqual baleen form annually (Lockyer 1981). Durham felt, however, that the steps in bowhead baleen occurred more often than once a year, and that three steps to the year was average. He did not have a hypothesis to explain the mechanism of formation of steps at such intervals.

Several of the baleen plates collected in 1986 show the steps very clearly along their length. Careful inspection reveals that the onset of a step marks a general thickening and widening of the plate. Following the initial thickening, the plate maintains its new width but smooths out and has less relief in the transverse ridging. On large whales such as 86WW1 and 86WW2, the steps are not accompanied by increasing width of the plate, but include the ridge and hollow pattern described by Scoresby (1820).

The stable isotope records for baleen plates revealed that each thickening in the plate, i.e. the beginning of a step, occurs in the late summer near the end of a 'peak' of  $\delta$  C-13 depletion. The period of maximum



increase in thickness occurs during the autumn when the whales are presumably moving westward across the northern coast of Alaska and into the Chukchi Sea. The roughness of the baleen then lessens, and the isotopic record indicates that this corresponds to the winter period. In some young whales the baleen grown in late winter is smooth and thinner than that grown in autumn, which may indicate poor feeding conditions. Figure 156 is a photograph of a plate from whale 86B3, an apparent six-year-old, with the isotopic record superimposed over the actual locations on the plate sampled. Note that the tip of the baleen was grown at a much faster rate than the base, and that the isotopic oscillations were much more subdued near the tip. Each year of life was accompanied by an increased amplitude in the oscillation (Fig. 156). By year six, the C-13 depletions were similar to the maxima observed in plates from other, older animals.

**Baleen Growth Rates.** --Table 55 lists the identification numbers and lengths of the whales whose baleen was sampled, and the ages of those whales as determined by isotopic oscillations in their baleen or by counts of annual ridges along the baleen plate. Table 55 also lists the Figure in which the isotopic data for each whale's baleen are presented.

The isotopic records for six young whales (ages  $3\frac{1}{2}$ -9 yr; lengths 7.6-10.7 m) are shown in Figures 151A, 157, 158. Four of these whales, including the aforementioned whale 86B3, show the gradual depletion in winter C-13 content, and all six show increases in the amplitude of annual oscillations with increasing age.

Also notable is the apparent decrease in baleen growth rates during the first half-decade of life. For the small whales 86KK1, 86B1, 86B3, and 86B4 (lengths 7.6-8.9 m), the baleen growth rates during the first isotopic cycle evident in the baleen were 49, 60, 46, and 35 cm/yr respectively. Growth rates decreased in later years, and by year 4 all animals had baleen growth rates of 24-27 cm/yr. This is near the value for adult bowheads, which averaged 17 cm/yr in 86WW1 (visually inspected), 19 cm/yr in 71B, 17 cm/yr in 86WW2, and 17 cm/yr in 86KK2. The trend for decreasing annual increments in baleen was also evident in whale 86KK3 (age about  $6\frac{1}{2}$  yr; length 10.4 m; Fig. 158). The trend was not evident in the largest of the six young whales, whale 86B7 (age at least 9 yr; length 10.7 m; Fig. 157D).

Baleen growth also varies from year to year, as shown by whale 86B4 (Fig. 157C). This whale shows 15 cm baleen growth in 1984-5 compared to an average growth rate of 24.5 cm/yr in the three years 1981-84. The 'winter baleen' for 1984-5 is more depleted of C-13 than that from the previous winter. It is tempting to speculate that the animal may have found poor feeding conditions during the autumn-winter of 1984-85. It is interesting that baleen from the 1985-86 winter showed a much greater enrichment in C-13, perhaps due to better winter feeding. The average growth rate of baleen during the eight months prior to death projects to an annual baleen growth rate of 23 cm/yr, a more typical rate. We conclude that young whales have a variable and often high baleen growth rate, sometimes >50 cm/yr in the first two years of life. The rate slows to about 20 cm/yr in animals over five years old. This agrees with the observations of Scoresby over 165 years ago.

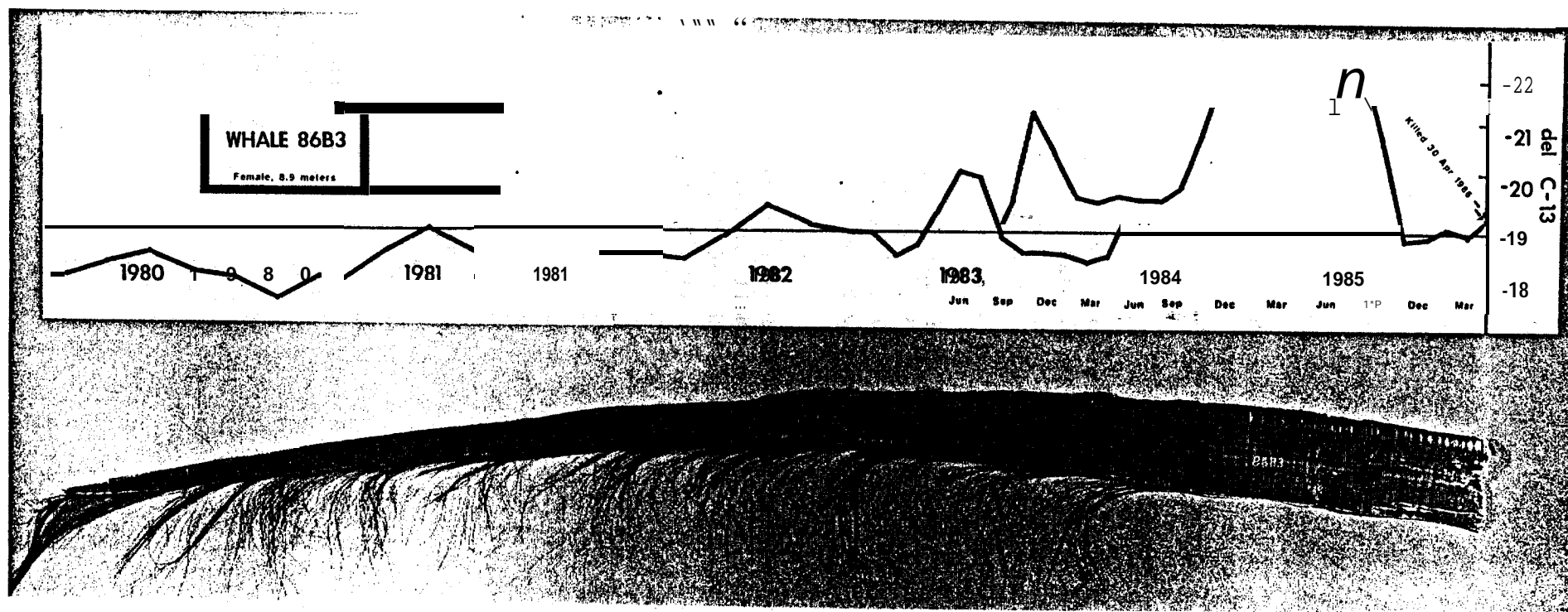


FIGURE 156. A baleen plate from bowhead 86B3 with the carbon isotope ratios at various points superimposed. Base of baleen (most recently formed portion) is at right in this Figure only. The year scale assumes that the C-13/C-12 oscillation is annual.

Table 55. Summary of isotopic data collected on bowhead whales during this project. Whales were taken at Wainwright (WW), Barrow (B) and Kaktovik (KK). The 'Baleen Age' column assumes that the period of the C-13/C-12 oscillation is annual.

Whale	Whale Length (m)	Sex	Baleen Age (yr)	Muscle del 13C	Visceral Fat del 13C	Blubber del 13C	Baleen del 13C Data	Baleen del 15N Data
Spring								
66B	9.7	M	7	-	-	-	Fig. 155	-
71Ba	16a	M	17.5	-	-	-	Fig. 152	-
85B?	-	-	-	-	-	-25.4	-	-
86B1	8.2	M	4	-19.4	-	-	Fig. 157A	-
86B2	8.7	M	1	-20.1	-25.8	-	Fig. 159A	Fig. 159A
86B3	8.9	F	6	-20.7	-	-	Fig. 157B	-
86B4	8.9	M	6	-19.6	-	-	Fig. 157C	-
86B5	8.1	M	2	-19.1	-24.4	H	Fig. 159B	Fig. 159B
86B6	12.3	F	12b	-19.7	-25.7	-	Fig. 157D	-
86B7	10.7	M	9	-20.0	-24.7	-	-	-
86WW1	15.9	M	17b	-18.8	-25.0	-	Fig. 161	Fig. 161
86WW2	17.7	F	20	-19.4	-25.8	-	-	-
85B5	7.0	F	-	-	-	-27.9	-	-
86KK1	7.6	F	3.5	-21.4	-27.6	-	Fig. 151A	Fig. 151A B
86KK2	17.1	F	>15c	-19.2d	-25.0	-	Fig. 163	-
86KK3	10.4	M	6.5	-21.4	-27.0	-	Fig. 158	-

a Season of kill undocumented but presumably spring based on baleen data. Length was estimated.

b Visual count of 'annual' ridges along plate.

c Ridges unsuitable for visual counting; isotopic ageing incomplete at this time.

d Two determinations gave -19.01 and -19.46.

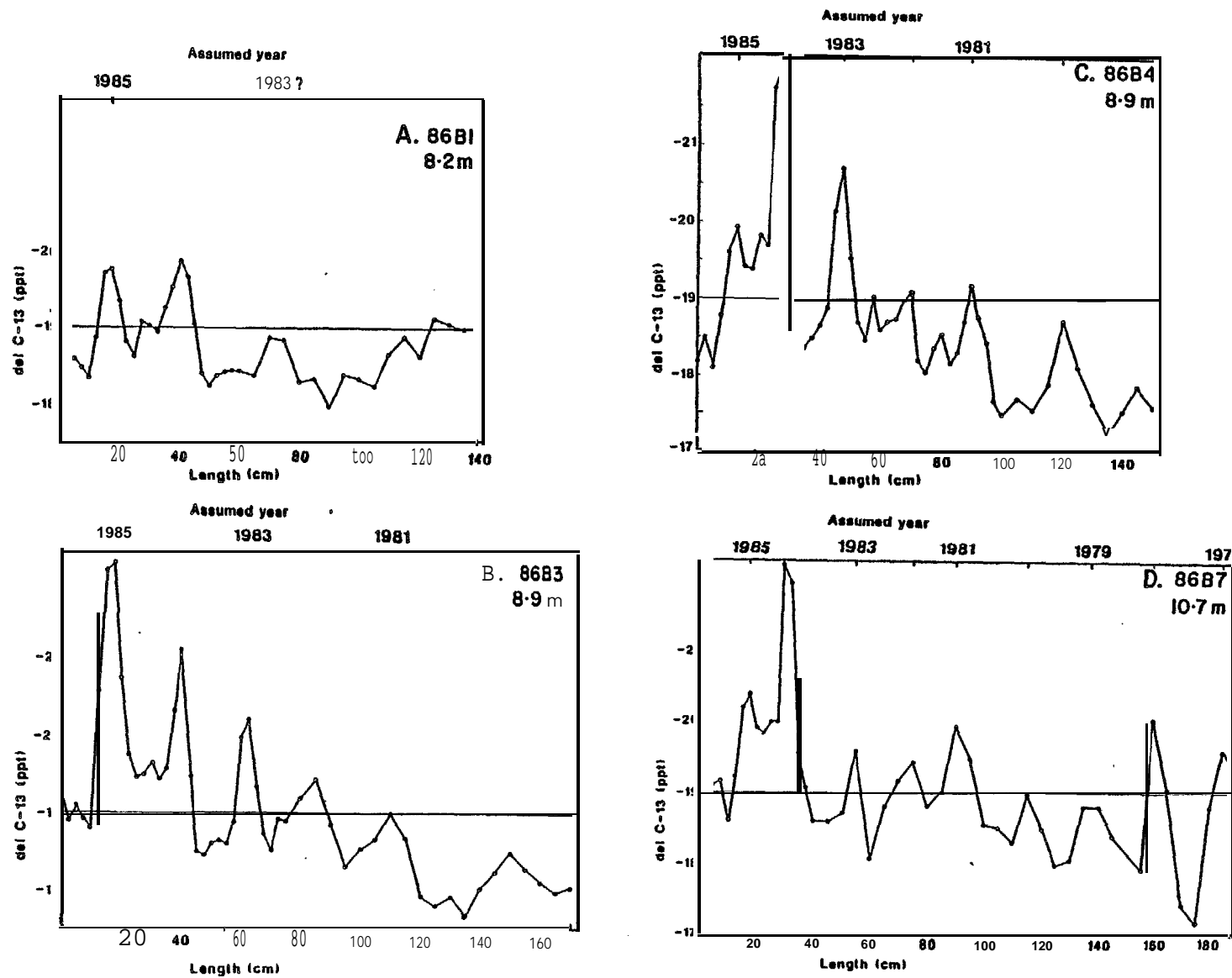


FIGURE 157. Carbon isotope ratios along baleen of four small whales taken at Barrow in spring 1986. (A) 86B1. (B) 86B3 (see also Fig. 156). (C) 86B4. (D) 86B7. The year scale assumes that the C-13/C-12 oscillation is annual.

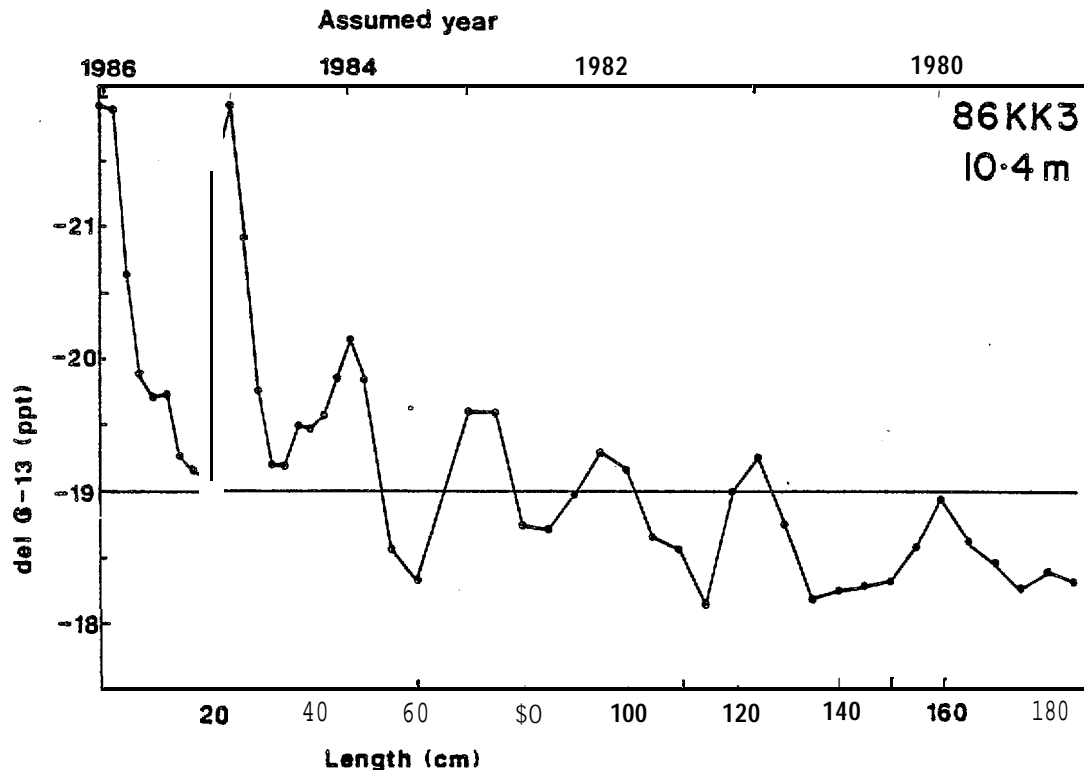


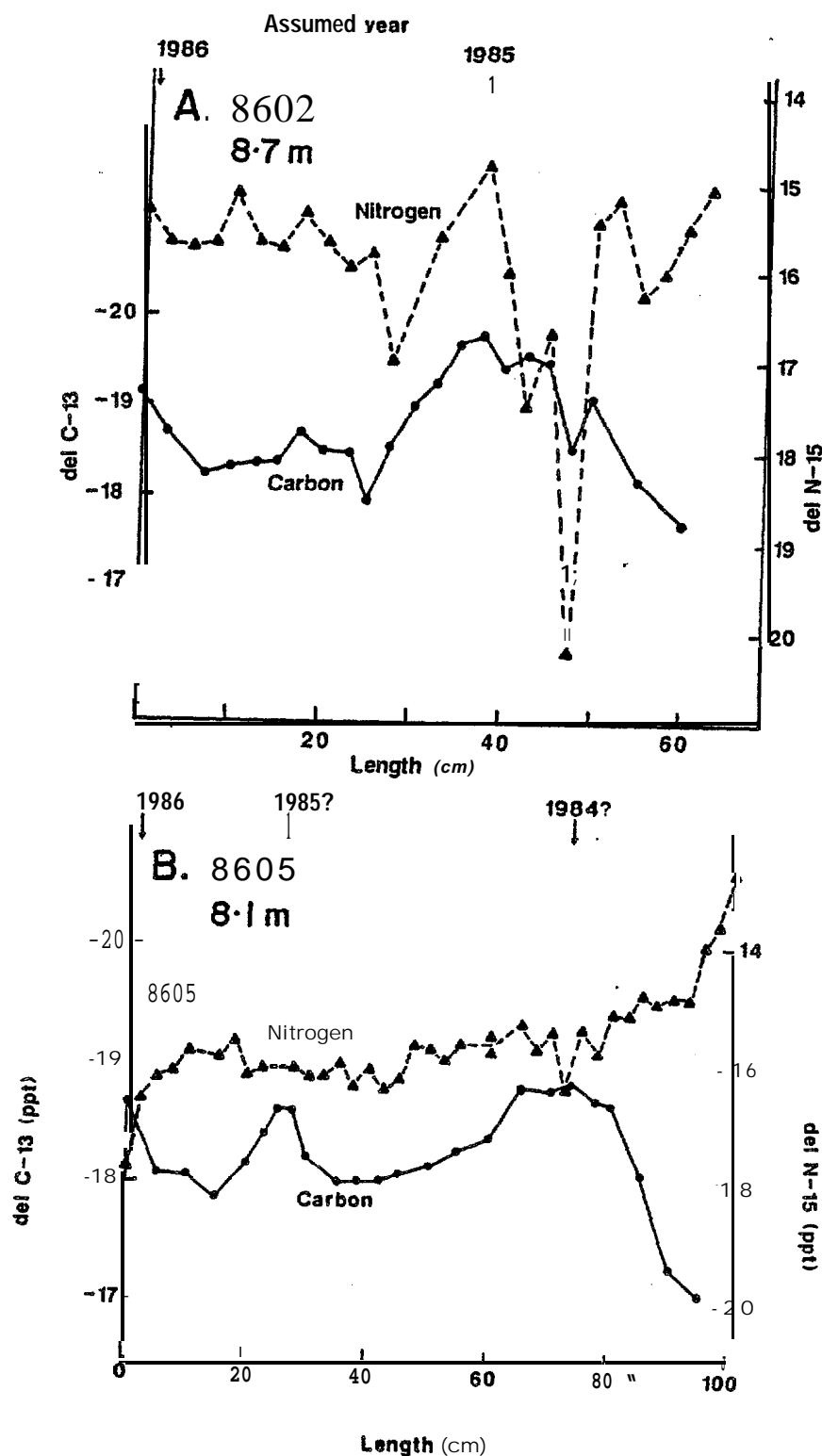
FIGURE 158. Carbon isotope ratios along baleen of bowhead 86KK3, a small bowhead taken at Kaktovik in autumn 1986. See Fig. 151 for data from another small whale taken at Kaktovik. The year scale assumes that the C-13/C-12 oscillation is annual.

Ingutuks.--The whales taken during the 1986 spring hunt at Barrow included two animals described as the morphological variant known as 'ingutuk'. Ingutuks are described in Nerini et al. (1984) as likely yearlings. The baleen plates from these animals were short and straight with very little relief in the transverse ridging.

The plate from whale 86B2 was only 65 cm in length and had a notch approximately 15 cm from the tip. Beyond the notch, the baleen was featureless with regards to ridging. This growth may have been fetal. Durham (1980) indicates that "total baleen length at birth, including baleen embedded in the gum, is about 18 cm. Only one C-13 cycle was present in the entire 65 cm length of the baleen plate (Fig. 159A).

The second ingutuk, 86B5, had a baleen plate 100 cm long, and showed 2½ low-amplitude C-13 peaks (Fig. 159B). This whale was probably two years old.

Life History Parameters.--The collection and interpretation of carbon isotope records in the baleen of bowhead whales provides the investigator with a 'baleen age' or a count of the number of years (C-13/C-12 oscillations) represented in the plate of baleen. Given the characteristic shapes and growth rates of the baleen isotope records in 1-3 year-olds, reasonable judgments and corrections apparently can be made for wear loss in whales up to 10-12 yrs of age. This would allow construction of an age-length curve, which would be very useful in estimating such critical parameters as gross annual recruitment rates and age at sexual maturity (cf. Davis et al. 1983, 1986b; Nerini et al. 1984). This type of work is currently being done by personnel of the U.S.



**FIGURE 159.** Carbon and nitrogen isotope ratios along baleen of two 'ingutuks' taken at Barrow in spring 1986. (A) For whale 86B2, the highly enriched N-15 value at position 48 cm may be due to a period of poor feeding conditions and protein assimilation within the whale. (B) Whale 86B5 does not show such extreme N-15 enrichment, although N-15 was somewhat enriched at the time of death. The year scale assumes that the C-13/C-12 oscillation is annual.

National Marine Mammal Laboratory, Seattle, using the techniques described herein.

Figure 160 provides a synopsis of whale lengths vs. 'baleen ages' (i.e. assumed minimum ages) of 20 bowheads for which we have, during this project, either determined an isotopic age ( $n = 11$ ) or estimated the age visually from the appearance of the baleen plates ( $n = 9$ ). For young whales whose plates show various small peaks that may result from winter feeding or mixed feeding and nursing (see below), we counted only what we believed to be the 'primary' annual oscillation. For some young whales (86B1, 86B5, and 86KK1) where there was uncertainty about one or more peaks, we considered the position of the peak relative to others, and the apparent rate of growth of the plate. Since wear is not taken into account, the ages shown are minima.

For the 9 small whales aged isotopically, the relationship between whale length and baleen length is statistically significant ( $r = 0.78$ , 1-sided  $p < 0.01$ ); the correlation is  $r = 0.97$  considering all 11 whales aged isotopically. However, the shape of the relationship is unexpected. If our few data for young whales are representative, bowheads apparently grow rapidly in length for about 1 year (including the pre-weaning period), then grow very

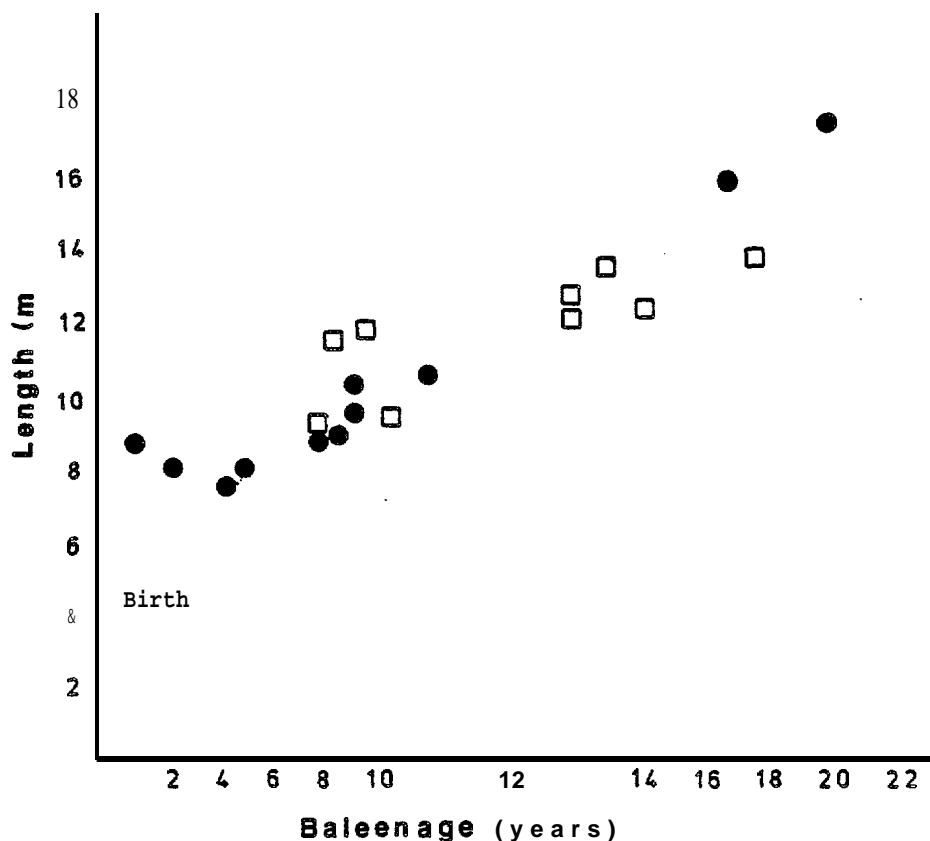


FIGURE 160. Length-'baleen age' relationship for whales examined in this study. Circles show data for whales isotopically aged ( $n = 11$ ; Table 55). Squares are based on visual inspection of baleen plates in the collection of the Los Angeles County Museum ( $n=9$ ). Ages are uncorrected for baleen wear at the tip, and undoubtedly are underestimates of actual ages for the larger whales.

little for the next 2-3 years, and finally **begin** a **period** of slow growth at an age of about 4 years. **This pattern is not typical** for mammals, and the apparent growth rate for bowheads **is** lower than that for the closely related southern right whale (**cf.** Whitehead and Payne 1981). It **is** noteworthy, however, that lengths of three additional young bowheads aged **isotopically** in another project were consistent **with** the pattern shown in **Fig. 160**: **79H3**, 9.1 m, 2 yr; **78B2**, 8.4 m, 5 yr; **79KK5**, 10.6 m, 8 yr (**Schell et al. in press**). Also, the one northern **right** whale whose baleen has been isotopically analyzed by us (**unpubl.** data) showed a baleen growth rate of  $32.5 \pm 4.1$  **cm/oscillation** over the **six isotopic** oscillations **evident in** the 1.95 m **baleen** plate. **This rate is** nearly double the baleen growth rate of medium-large bowheads, suggesting that growth of **right** whales **is** more **rapid** than that **of** bowheads.

Recent interpretations of **photogrammetric** data on the-length composition of the population (**Davis et al. 1986b**; Nerini et al. 1987) are inconclusive about growth rate, but are not inconsistent with our suggestion that yearling bowheads are 8-9 m long. **Photogrammetric** data for individually identified bowheads seen at intervals of 1-4 years also suggest that growth of **subadults is quite** slow (**Davis et al. 1986b**, p. 170 **ff**). Nonetheless, the **apparent** pause **in** growth at ages 1-4 years (**Fig. 160**) **is** very surprising and needs further investigation.

Our results to date indicate that determination of the stable isotope ratios along a **piece** of baleen **is** not essential to determine the age. of the whale. The 'steps' evident along the plates were postulated to be annual "markers over 165 years ago. **Until** recently, however, there was no independent means of verifying the assumed annual nature of the 'steps'. The radiocarbon event due to atmospheric testing of nuclear weapons over 20 years ago provided that method. 'Any of the longer baleen plates collected in the late 1960's would be expected to include the sharp rise in C-14 activity. The **position** along the baleen where **that** increase occurred could have **been** related to the visually-apparent steps as well as to the stable **isotope oscillations**. Thus, at any **time in** the past 20 years, the **periodicity** of the **visible** steps could have been investigated **via** radiocarbon analysis without consideration of stable isotope data. If **this** had been done, **it might** have been possible to construct a length-age curve from visual **inspection** of baleen plates. However, our radiocarbon and stable isotope data, taken together, provide stronger evidence that the 'steps' are annual markers. If these results are accepted, then the ages of **subadult** whales harvested **in** future years can **be** estimated by **visual** inspection of the baleen.

#### Stable Isotopes in Baleen in Relation to Feeding

**Bowhead** whales apparently continue to grow baleen during winter, based on the differences in isotopic patterns in baleen of whales killed in spring vs. autumn. Food from areas outside the eastern Beaufort Sea is apparently used in producing the 'winter baleen', based on the observed changes in C-13 content along baleen plates, the temporal pattern of these changes, and the **observed** geographic trend in C-13 content of zooplankton. The isotopic content at each point along the baleen represents the isotopic content of the energy source used when that baleen was formed, with an added C-13 enrichment due to fractionation by metabolic processes within the animal. This energy source could be either prey that was being consumed when the baleen was formed, or energy mobilized from stored reserves within the whale. In either case,



analysis of the isotopic record in the **baleen** has the potential to provide information about the energy sources used over much of the lifetime of the whale.

No definite **explanation can** be identified for some of the observed patterns of isotopic variation in baleen. However, the data **allow us to** propose hypotheses that may provide a focus for future research.

**Isotopic Shifts in Young Whales.**--As shown earlier, the **C-13** content of **baleen often** decreases as **young** whales become older, and the **amplitude** of the annual oscillations in C-13 content increases (Fig. 151A, 157, 158). Any interpretation of these trends is **speculative**, but some hypotheses **can** be formulated. These are not mutually exclusive; several factors may be involved.

The most **distal baleen** present in a young whale is formed either before **birth** or before weaning, and the carbon contained therein comes from the mother. (The **foetal** baleen may **quickly** wear away, but the **pre-weaning** baleen persists longer.) Baleen is about 18 cm long in neonates, including the portion **within** the gum (Durham 1980). The time of weaning is not known, but may be toward the end of the first year after **birth**. The baleen being **formed** at any one time presumably incorporates carbon acquired from prey over some **unknown** period of time. Perhaps this 'averaging' period is shorter in the case of **whales** feeding **for** themselves than for **calves** acquiring carbon from their mothers. If so, the isotopic oscillations **might be less** pronounced in **baleen** formed before weaning,

The decreasing C-13 content of baleen formed during the first few years of **life** might be a **result** of changes in feeding locations in prey **types**, or both. Both of these factors affect the **C-13** content of **zooplankton**. During **late** summer in some years, many **small bowheads** feed in shallow waters close to shore **along** the **coast** of the south-central Beaufort Sea (see 'Bowheads' section, p. 311 ff, 360). In 1985-86, the predominant prey type in these areas was **copepods**, mainly **Limnocalanus macrurus** (see 'Zooplankton and Hydroacoustics' section, p. 198-204, and Bradstreet and Fissel 1986; Bradstreet et al. 1987). Since **copepods** in these areas are depleted of **C-13**, we would expect the baleen of **small whales**, or at **least** the baleen laid down in late summer, to have **low C-13** content. Thus, it was unexpected that **C-13 content** tended to decrease with increasing **age**.

Perhaps the changes are partly attributable to an improved efficiency of filtration by the growing baleen in the young whale's mouth. During the first **post** weaning years, the animal has short baleen and might be **dependent** upon **larger zooplankton** such as **euphausiids**, **mysids**, and **amphipods**. These organisms **typically** are enriched in **C-13** compared to **copepods** in the same environment. As the **baleen plates** of the **subadult** whale become **longer** with growth, it might **obtain** a larger fraction of its food from C-13-depleted **copepods**, including those in shallow coastal waters. The **annual C-13** oscillations in baleen might increase in amplitude with age if **copepods** are the dominant prey only during **late** summer and early autumn. Unfortunately, the available evidence from **whale** stomach contents is insufficient to support or disprove this speculation.

Another possibility is that, in subadult bowheads, the progressively greater C-13 depletion in the baleen formed in recent years is a result of progressively greater utilization of inshore waters where copepods predominate. In 1983-86, many subadult bowheads fed along the Yukon coast from mid-August through much of September (Richardson et al. 1985a, 1987; Davis et al. 1986a,b; Cabbage and Calambokidis 1987a; this study). In 1986, this nearshore feeding by subadults extended west into the Eastern Alaskan Beaufort Sea. Bowheads of unknown sizes concentrated along the Yukon coast in late summer during some years in the 1970's (Fraker and Bockstoe 1980), but bowheads did not concentrate there in 1980-82 (Richardson et al. 1985a, 1987). It is not known where subadult whales fed in the late summers of 1980-82, or the C-13 content of their diet in those years. However, many subadults fed in nearshore waters in 1983-86, and for 1985-86 we know that they were feeding mainly on Limnocalanus macrurus, which has a low C-13 content. This may at least partially account for the decreased C-13 content in baleen laid down in the summers of 1983-86 relative to that laid down in 1980-82.

**Winter Feeding.**--The occurrence in 'winter baleen' of a C-13-enriched isotopic ratio (typical of zooplankton from the western part of the bowhead's range--Fig. 149) suggests that feeding occurs in late autumn or winter. However, these data must be interpreted cautiously. The baleen data alone do not prove that bowheads acquire a significant proportion of their annual energy intake in the Bering Sea:

1. If limited feeding occurs in late autumn and winter, carbon obtained from this feeding might appear in the baleen without a major contribution of energy for maintenance of the remainder of the whale.
2. It is possible that some of the carbon laid down in baleen during winter comes from mobilization of reserves stored in the western Beaufort Sea or Chukchi Sea in autumn. Zooplankton from at least some of those areas is also enriched in C-13 relative to zooplankton from the eastern Beaufort Sea. Also, the autumn diet would be further enriched in C-13 if, as some evidence suggests, bowheads consume more euphausiids (or other omnivorous or predatory animals) in autumn than in summer (Fig. 149). We do not have enough data on isotopic ratios in zooplankton from the northern Bering Sea to determine whether prey from that area can be distinguished, on the basis of isotopic content, from prey in the western Beaufort or Chukchi seas (Fig. 149).

Nonetheless, the baleen clearly records a regular (apparently annual) oscillation in carbon isotope ratios. A substantial fraction of the baleen--that laid down in late autumn, winter and spring--contains isotopic ratios which, when metabolic fractionation and enrichment is taken into account, could not be obtained from any known prey in the Canadian or Eastern Alaskan Beaufort Sea. Furthermore, the presumption that there is some feeding in winter is greatly strengthened when the baleen data are considered in context with observed changes in muscle and fat isotope abundances, at least in subadults (see later).

As young whales age, there is a trend toward decreasing C-13 in the baleen laid down in winter (the 'valleys' in our graphs) as well as the aforementioned similar trend in summer (the peaks). The trend in winter might

**reflect** progressively increased winter feeding on **copepods** with age. Alternatively, it might **reflect** mobilization in winter of the progressively more C-13-depleted carbon stored in recent summers.

There are multi-year trends in older whales as well, sometimes in one direction and sometimes in the other. Whale 86WW2, a 17.7 m female taken at Wainwright, contained a 20-yr feeding record in its baleen plates (Fig. 161). For the eight years prior to 1985-6 (positions 20-150 cm from base of baleen), the C-13 values in winter had been decreasing. Its baleen revealed other periods with sharp changes in winter isotope ratios, separated by periods of slower multi-year trends either toward enrichment or depletion. These phenomena were also evident in whale 71B, the one other large and old whale whose baleen was fully analyzed (Fig. 152).

The trends observed in these older animals may reflect year-to-year changes in oceanographic regimes. If so, the resulting isotopic changes in prey organisms could affect large segments of the total population. In young whales, these broad-scale changes may be superimposed onto the changes in isotopic composition that occur with increasing age. A larger sample of baleen plates from older whales would need to be analyzed in order to search for possible parallel trends in different whales.

Careful inspection of the winter portions of the curves shows that a small peak (i.e. a period of slight C-13 depletion) is often present within the period of maximum C-13 enrichment. This peak seems to occur between about January and April, based on its position relative to the apparent autumn and 'spring portions of the C-13 cycle. Occasionally, these presumed midwinter peaks are very pronounced, such as in the apparent 'winter of 1985-86' in whale 86KK1 (Fig. 151A). For that whale, isotopic depletion in the mid-winter period of 1985-86 was comparable in magnitude to that in the summers of 1983-84, when this whale was apparently a calf and yearling.

The presumed winter peaks might be due to a prey shift from secondary consumers (i.e. euphausiids, amphipods) to primary consumers (i.e. pelagic copepods). Alternatively, the peak might indicate a mid-winter period of reduced feeding and utilization of fat reserves laid down in summer and thus depleted of C-13. Since this peak seems to coincide with the period of maximum winter ice extent, it may represent a period when most whales are forced south, perhaps off the continental shelf, by the expanding ice. If this is the explanation, this secondary isotopic peak might not be present every year or in every whale, since the maximum extent of winter ice cover varies among years.

Similarities Between Whales.--The isotopic records along the baleen plates collected from whales 86B3, 86B4 and 86B7 can be interpreted as providing evidence that feeding patterns for the years 1983-86 were similar in these young whales (Fig. 157). In 86B4 and 86B7 especially, the relative isotopic abundance patterns match very closely. Perhaps these animals used similar feeding areas in both summer and winter, and acquired similar relative amounts of food from each habitat. The documented shift in summer feeding areas of many subadult whales between 1980-82 and 1983-86 was mentioned earlier. This might account for some of the between-whale similarities in the summer pattern.

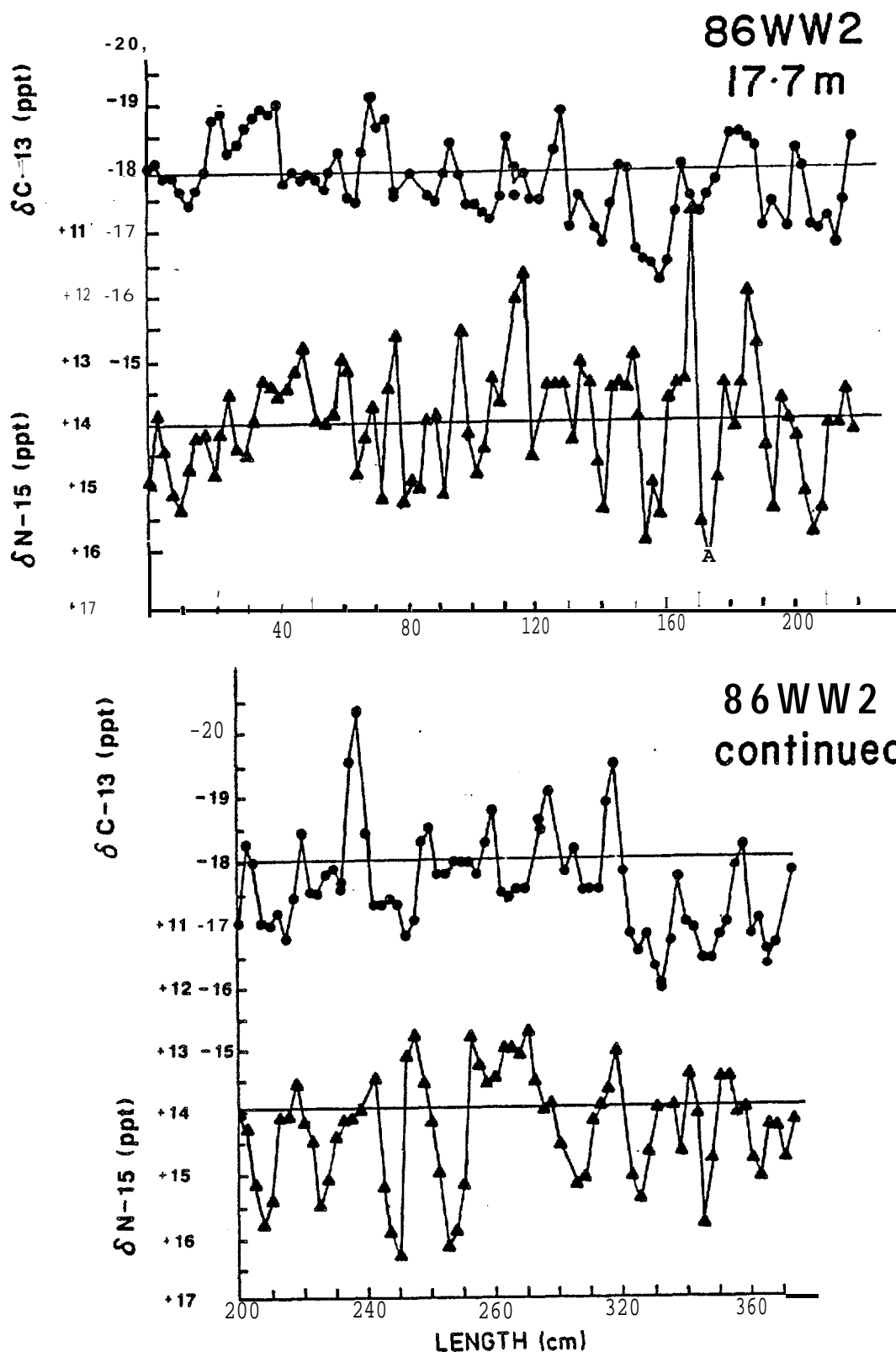


FIGURE 161. Carbon and nitrogen isotope ratios along baleen of bowhead 86WW2, a large whale taken at Wainwright in spring 1986. Note that the carbon reference line is at -18 ppt instead of the -19 ppt level used for all other whales.

The **high** (C-13-depleted) summer peaks of 1984 were **followed by a winter** of relative C-13 depletion. Data from whales **86B1, 86B3, 86B4, 86B7 and 86KK3** reveal that, for **all** of these young whales, the baleen formed in the winter of 1984-85 was depleted in C-13 relative to that from the winter of 1983-84 (Fig. 157, 158). The difference between winters must have arisen from a consistent difference in the C-13 content of the food and/or stored carbon used in different winters. It would be unlikely that physiological processes would produce alterations in baleen isotope content with such similarity in five whales of varying ages.

Nitrogen Isotopes and Starvation.--Nitrogen isotope ratios also can provide information about energy flow in ecosystems (Ehleringer et al. 1986). We analyzed the N-15/N-14 ratio along the baleen of four whales (Table 55). The following interpretation of these data is speculative, given the scarcity of information about the causes of N-15 enrichments in organisms.

The nitrogen isotope ratios for the two 'ingutuks' showed very different patterns (Fig. 159). Whale 86B2 showed a very sharp enrichment in N-15, the heavier isotope, during its first spring and summer season in 1985. Perhaps this was a period of fasting by the animal. A lack of protein intake would probably result in preferential loss of the lighter isotope during nitrogen metabolism. Such a change might be expected after weaning. However, the associated C-13 data (Fig. 159A) suggest that the period of N-15 enrichment was in mid-year, when bowhead calves continue to accompany their mothers. In contrast, no period of N-15 enrichment was evident in the other ingutuk (Fig. 159B).

An enrichment in N-15 also occurred in whale 86KK1 early in its life (Fig. 151). In this case, the period of N-15 enrichment was more prolonged than found in whale 86B2; this might coincide with a post-weaning period during the animal's first winter. Because the lipids in blubber contain much more carbon than nitrogen, starvation would produce a nitrogen demand much earlier than an energy demand.

Alternatively, the oscillations in the nitrogen records may be due to other less obvious factors such as water stress in recently weaned whales or in the lactating females from which calves were receiving milk. There are large enrichments in collagen N-15 in animals from arid regions (Heaton et al. 1986; Ambrose and DeNiro 1987). Analogous situations may arise in marine mammals that lose large amounts of water in a salt water environment. The heavy freshwater demands on a lactating female, or the water stress in young animals at weaning, may lead to preferential renal elimination of the light isotope (N-14) during the processing of nitrogenous excretion compounds.

These interpretations are not substantiated; they are mentioned only as possible mechanisms that might account for the observed changes in the relative abundance of the N-15 isotope. The physiological and environmental causes of N-15 enrichments are still in debate.

Within the marine environment, the isotopic ratio of nitrogen can vary as a result of changes in the relative amounts of upwelled nitrate versus ammonia incorporated into the phytoplankton that support the food chain. Data on the N-15 content of zooplankton are not presently available for the range of Western Arctic bowheads. Such data would probably assist in interpreting the

causes of the observed perturbations in N-15 in the baleen. Data on the geographic and **trophic** variations in **C-13** within **zooplankton** assisted in interpreting the C-13 oscillations in baleen.

#### Seasonal Shifts in Isotope Ratios In Bowhead Muscle and Fat

If whales feed to a significant extent during late autumn and winter in the western Beaufort, **Chukchi** and Bering Seas, where the **zooplankton** contain more **C-13** than in the eastern Beaufort Sea, bowhead tissues should contain more C-13 in spring than in autumn. Conversely, if there is little late autumn or winter feeding, bowhead tissues **should** have similar isotopic content in spring and autumn. If bowheads feed extensively in winter on the same types of **zooplankters** as are consumed in summer, the postulated seasonal change in isotopic composition of bowhead **tissues should** be similar in magnitude to the geographic change in the isotopic composition of **zooplankton**. However, if a major change in prey type occurs between summer and winter, a **larger** shift is possible. This could occur if the primary prey changed from **copepods** in summer to omnivorous or carnivorous zooplankton (e.g. **euphausiids**, **amphipods**, or **chaetognaths**) in winter.

In mammals, the carbon in different tissues turns over at different rates. Skeletal muscle, which typically has about a 30 day turnover time in laboratory mammals, would be the preferred tissue for studying isotopic changes. Carbon in oil from the blubber layer may have a much longer turnover time since its functions include insulation as well as energy storage. Ackman *et al.* (1975) found that the percentage of unsaturated fats increased near the inner layers of blubber and concluded that they represented newer and more mobile tissue. They felt that the **subdermal** fats had much longer residence times than the inner layers, which appeared to be used **more** for energy **storage** and less as insulating tissue. In mammals, muscle tissue is recycled *at a* more uniform rate than fat (Gordon 1968; **Dowgiallo** 1975). We focused on muscle tissue and on -visceral fat; the **latter** was believed to be more **likely** than blubber to be mobilized in periods of poor feeding.

The 1986 **whale** hunt yielded the first good collection of samples for comparison of the **isotopic** composition of **muscle** and visceral fat *at the* ends of the winter and summer seasons. Data were available from three **whales** taken at **Kaktovik** in autumn 1986, and from nine whales taken at Barrow and Wainwright in spring 1986. Baleen samples from most of these whales were also **analyzed** for **isotopic** content (Table 55). For these whales, the temporal pattern of isotopes in the baleen can be used to help evaluate the food sources on which the whale **relied while** the carbon in the muscle and **fat** tissues was being accumulated. Since the **muscle** and blubber samples analyzed prior to 1986 (see **Schell** 1986, p. 303-306) were from poorly documented samples with no concurrent baleen record, the calculation of carbon turnover was limited to data from the 1986 samples.

In northbound **whales** harvested in spring, **del** C-13 values in muscle tissue ranged from -18.8 to -20.7 ppt (Fig. 162, **Table** 55). About 4½ months later, values in the two **small** whales taken *at* Kaktovik were both -21.4. However, the average value for the third **Kaktovik** whale (86KK2) was -19.2, similar *to* results from **whales** taken in spring.

Results from the visceral fat samples showed a very similar pattern, including the C-13 depletion in whales 86KK1 and 86KK3 but not 86KK2 (Fig. 162; Table 55). However, during both seasons, C-13 values were about 5 ppt lower in visceral fat than in muscle. This was expected; lipids normally possess lower C-13/C-12 ratios than protein or carbohydrate (McConnaughey and McRoy 1979; Tieszen et al. 1983).

The isotope composition of the recently-formed baleen from the three Kaktovik whales (Fig. 163) provides a possible explanation for the differences in isotopes in their muscle and fat tissue. In the two small whales, baleen laid down shortly before death contained low amounts of C-13, indicating that they had fed heavily in the eastern Beaufort where zooplankton is depleted of C-13. The baleen of whale 86KK2, however, showed a much smaller 'peak' in the C-13 record shortly before death. That whale apparently had either fed very little in the eastern Beaufort Sea in the summer of 1986, or fed on prey more enriched in C-13 than any zooplankton found by us in the eastern Beaufort Sea. It should be noted, however, that we have no zooplankton samples from Amundsen Gulf or from offshore waters of the Canadian Beaufort Sea. Large bowheads are known to frequent some of these areas. Whale 86KK2 was large.

The results from whale 86KK2- may be indicative of a general pattern of differences in diet between large and small whales. The  $\delta$  C-13 values in the baleen laid down by whale 86KK2 in the summer of 1986 were  $>-19$  ppt for the entire summer, consistent with the muscle value. These values were similar to those in the baleen of whales 71B (Fig. 152), 86WW2 (Fig. 161), and 86WW1 (not shown), the other large animals that we have studied. The baleen of these large whales was about 1 ppt more enriched in C-13 than that of young ( $<10$  yrs) whales. Interestingly, muscle from two large whales harvested at Kaktovik in the autumn of 1981, 81KK2 and 81KK3, was also enriched in C-13 ( $-18.7$  and  $-19.0$  ppt, respectively) and similar to the value in muscle from a large whale taken at Wainwright in the spring of 1981 ( $-17.95$  ppt; Schell et al. 1984; Schell 1986). All of these 1981 whales were adults  $\geq 14$  m long. Thus the stable isotope data suggest that the types of prey consumed in summer may differ between large and small whales, or alternatively that large adult whales do not do much feeding in parts of the eastern Beaufort Sea where zooplankton are depleted of C-13.

For small whales, the differences in the isotopic composition of muscle and fat tissues in spring and autumn suggest that these whales may feed extensively in the late autumn-winter-early spring period (i.e. after passing Kaktovik in autumn and before arriving at Wainwright or Barrow in spring). In contrast, for large whales there was no seasonal difference between whales killed in autumn (86KK2, 81KK2, 81KK3) and spring (86WW1, 86WW2). Based on this evidence, only the smaller whales were considered in the following calculations of the turnover of carbon that occurred during summer and winter.

#### Carbon Turnover Rates in Summer and Winter

Calculation of energy dependencies requires that the isotopic abundances in the food be sufficiently different in time or space to allow approximation via the equation

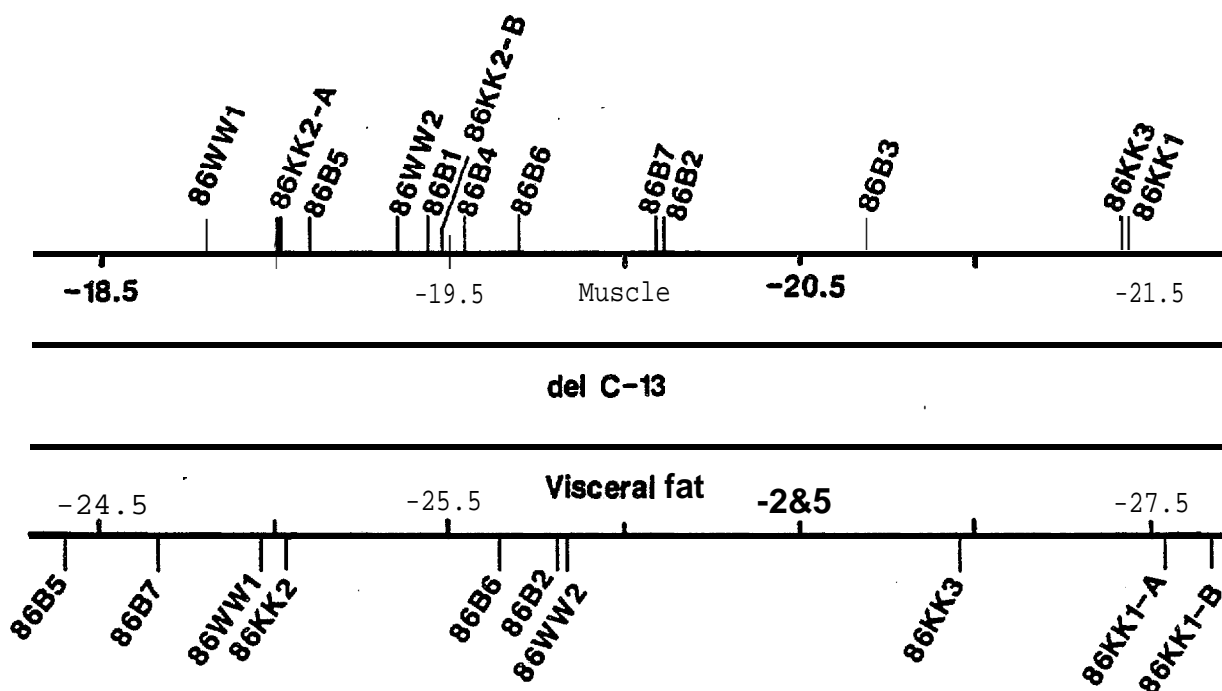


FIGURE 162. Carbon isotope ratios in muscle and visceral fat tissue from bowheads taken in spring 1986 (WW and B) and autumn 1986 (KK). The -A and -B notations refer to replicate determinations.

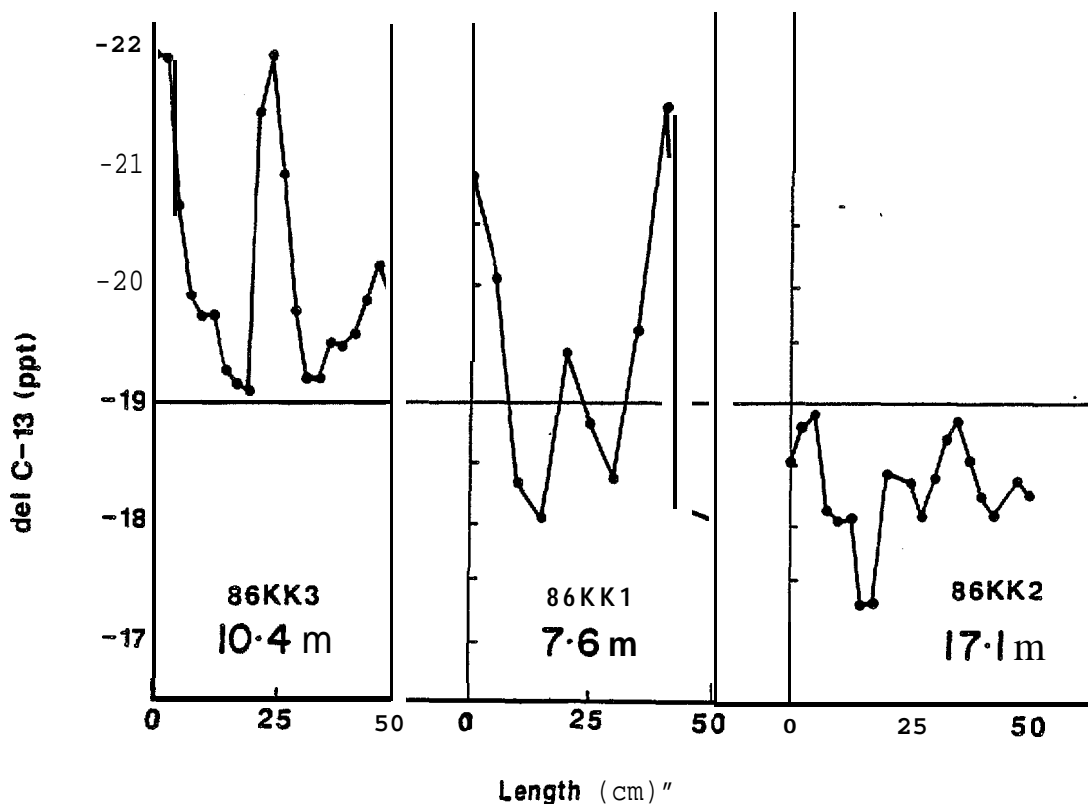


FIGURE 163. Carbon isotope ratios in the most recently formed baleen of the three bowheads taken at Kaktovik in autumn 1986. This baleen was formed between winter 1984-85 and autumn 1986.



$$\delta^{13}\text{C}_t = (\delta^{13}\text{C}_{t=0} - \delta^{13}\text{C}_f)e^{-kt} + \delta^{13}\text{C}_f$$

or

$$\ln [(\delta^{13}\text{C}_{t=0} - \delta^{13}\text{C}_f)/(\delta^{13}\text{C}_t - \delta^{13}\text{C}_f)] = kt$$

where the C-13 content at time=0 and time=t is known for the organism and the food f. The constant k is the calculated turnover rate and 1/k is the calculated turnover time for the C-13 in the organism.

Food isotopic values were estimated from the baleen isotope records, adjusted by -1.0 ppt to account for internal fractionation in the formation of keratin (Tieszen et al. 1983). Since feeding conditions were assumed to deteriorate in late winter, winter food values were averages for 3 months prior to the death of whales taken in spring. The assumed isotopic composition of food in summer was based on the baleen being formed at the time of death in fall, since this is the period of maximum zooplankton stocks. The values used in the equations are listed in Table 56.

The isotopic ratios in muscle and fat during spring were used as starting points for the summer turnover calculations. Ratios from autumn whales were used as the starting points for the winter turnover calculations.

The calculated turnover times (Table 56) are probably overestimated due to the long sampling interval between the spring and autumn whale hunts. The calculated turnover time for muscle carbon in small bowheads is similar in summer and winter. The actual summer feeding period may be shorter than the assumed 4½ months, since zooplankton stocks are low when the whales arrive. Thus, the summer turnover rate may be higher than calculated and the turnover time lower. Similarly, the winter turnover rates reflect the optimum fall feeding conditions. The autumn-spring interval may be very heterogeneous with regard to food availability and turnover rate. Other than reported feeding on euphausiids near Barrow in autumn (Lowry and Frost 1984) and benthic prey, mainly gammarid amphipods, in the St. Lawrence Island area in late winter (Hazard and Lowry 1984), nothing is known of actual feeding activities in late autumn, winter or early spring.

"Table 56. Average C-13 values in muscle, baleen, and food as used in calculations of carbon turnover times in small bowhead whales during summer and winter. Turnover time in months is the reciprocal of turnover rate (i.e. 1/k).

	$\delta^{13}\text{C}$			Turnover k ( $\text{t}^{-1}$ )	Turnover Time (months)
	Muscle	Baleen	Food		
Summer	-19.8	-18.4	-22.4	0.21	4.8
Winter	-21.4	-21.4	-19.4	0.21	4.8

The method used to calculate the carbon turnover time in visceral fat from small bowheads was similar. However, normalizing the fat  $\delta$  C-13 values based upon baleen values presents difficulties if the above values for C-13 content of food are correct. The measured C-13 content of the lipids in small bowheads is about -27.3 in autumn (Fig. 162). The assumed C-13 content of the summer food is about -22.4, based on analyses of baleen. This difference is greater than the accepted 3 ppt value for lipid synthesis fractionation (Tieszen et al. 1983). However, the measured C-13 values in copepods are near -25 ppt (Fig. 146-147), which is reasonable in relation to the measured values in bowhead lipids. If the -25 ppt value for food is used in the calculations, the baleen keratin requires an internal fractionation correction of near 4.5 ppt, which is an unexpectedly high value.

If an internal fractionation value of -5 ppt is assigned for the 'food to visceral fat' transfer, the calculated carbon turnover rates in visceral fat of small bowheads are  $k = 0.69$  in summer and  $k = 0.17$  in winter (turnover times of 1.4 mo and 5.9 mo, respectively). These rates imply that more food is acquired in summer than in winter, in contrast to the muscle turnover calculations. The extreme sensitivity of  $k$  to the C-13 values selected for the average food, and to the correction factor for internal fractionation, makes calculation of these summer and winter rate constants inconclusive with so few data and such long sampling intervals.

The answer for this apparent dilemma may be that the small whales derive most of their lipids from the oil-rich copepods and derive most of their proteinaceous materials from other prey that are more enriched in C-13, such as euphausiids, mysids or amphipods. "

In any case, the limited samples currently available suggest that the carbon in the muscle and visceral fat of small whales is almost entirely replaced during both summer and winter. This may mean that the intake of food by subadults is of the same magnitude in summer and winter. We emphasize that this conclusion is based on a comparison of two small whales killed in autumn vs. seven subadult whales killed in spring. Larger sample sizes are obviously desirable. For large whales, the sample sizes are even smaller (3 fall, including the two 1981 whales; 3 spring, including one 1981 whale). The results from large and small whales were quite different, with no obvious change in carbon isotope composition of muscle or visceral fat between spring and fall in large whales. Several hypotheses regarding the feeding locations of large bowheads could be suggested, but speculation is premature until the isotopic composition of prey is determined for the winter range, unsampled areas of the Beaufort Sea, and Amundsen Gulf. In any case, the results suggest that young bowheads may feed for a larger fraction of the year than do older bowheads.

#### Other Applications of Baleen Stable Isotope Records

The baleen whales all contain baleen plates that are potentially useful in assessing migration and feeding patterns. To date we have not attempted any detailed investigation of whales other than bowheads. However, we obtained stable isotope records from one gray whale and one fin whale (Fig. 164).

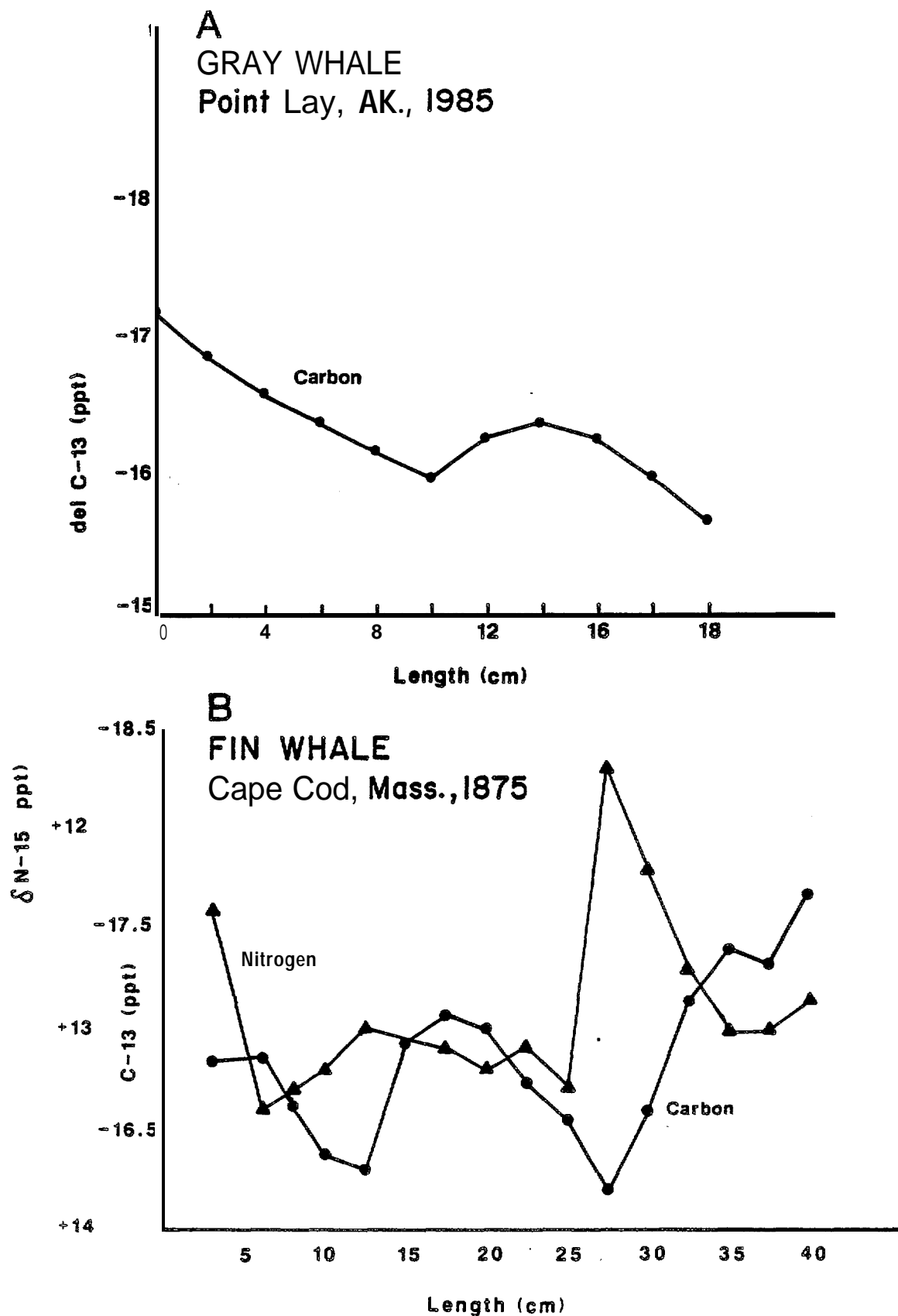


FIGURE 164. Isotope ratios along baleen from (A) a subadult gray whale killed by orcas at Point Lay, Alaska, July 1985, and (B) a fin whale stranded on Cape Cod, Mass., 1875.

**Gray Whale Baleen.**--Gray whale baleen was obtained from an animal killed by killer whales near Point Lay, Alaska ( $69^{\circ}40'N$ ,  $163^{\circ}30'W$ ), in July 1985. The plate was only 20 cm long. However, it revealed decreasing  $\delta C-13$  values from its tip to its base, with a period of enrichment near the center (Fig. 164A). The C-13 enrichment near the tip is greater than found in any bowhead baleen and might reflect feeding in warmer water and/or on different prey types. The marked depletion toward the base of the plate may result from northward migration to Alaskan waters. The final values of carbon isotope abundances are similar to those found in the 'winter baleen' of bowhead whales.

**Fin Whale Baleen.**--A single piece of fin whale baleen was obtained from the Smithsonian Institution for another study. This 40 cm sample was from a whale stranded on Cape Cod, Mass., in 1875. The isotopic records for nitrogen and carbon are shown in Figure 164B. If the growth rate of the baleen was near 20 cm/yr, as in bowheads, the record spans almost two years. No information is available as to the season of death, but the oscillations in the C-13 record, if resulting from temperature effects, indicate that the animal died in the fall. [Prey from warmer waters tend to be more enriched in C-13 (Rau et al. 1982).] The  $\delta C-13$  values are indicative of feeding on prey relatively enriched in C-13; the values are not far from those observed in the 'winter baleen' of bowheads.

The nitrogen record for the fin whale is out of phase with the carbon record (Fig. 164B). Since nothing is known of the isotopic composition of the prey of this whale, we cannot comment on the trace other than to note that the N-15 values are similar in range to those noted in bowheads.

### Summary and Conclusions

The goal of the isotope work was to use the variations in natural abundances of carbon isotopes in zooplankton and in bowhead whale tissue to estimate the relative importance of various feeding areas, emphasizing the question of winter feeding. The isotopic data obtained in this project provide insight into both the energetic of bowhead whales and the physical/chemical environments used by these animals and their prey. In addition, the discovery of regular variations in carbon isotope ratios along bowhead baleen has provided a potential method for ageing young whales, which would provide insights into life history. We analyzed baleen and/or tissue samples from 16 whales during this project, ranging from yearlings to large adult animals (Table 55). Muscle and/or blubber from five other whales had been analyzed previously (Schell et al. 1984; Schell 1986, p. 30S). From the analyses conducted to date, several conclusions can be drawn.

1. The ratio of stable carbon isotopes ( $C-13/C-12$ ) in zooplankton varied across the range of bowhead whales. C-13 was more common in zooplankton from the western Beaufort Sea and (probably) northern Bering Sea than in zooplankton from the central and eastern Beaufort Sea.
2. The ratio of stable carbon isotopes also differed between primary consumers (e.g. copepods) and omnivores or secondary consumers (e.g. euphausiids, chaetognaths, amphipods). The latter groups contained relatively more C-13, as expected from studies elsewhere.

3. **In young bowheads**, the geographic and **trophic** differences in carbon isotope composition of zooplankton are apparently manifested as seasonal isotopic shifts **in** the muscle and visceral fat. The muscle and visceral fat of young **whales** contained relatively more **C-13** in spring than **in** autumn. **If** these small samples were representative, the results indicate that **young whales** acquire a significant fraction **of** their **annual** food intake during the **late autumn-winter-early spring** period **while** they are not in the **eastern** or central **Beaufort** Sea.
4. **In large** whales, carbon isotope ratios in **muscle** and visceral fat were similar in spring and autumn. The **muscle** tissue was relatively enriched in **C-13** in both seasons, suggesting that most of the carbon **in** this muscle may not have come from the southeastern Beaufort Sea. The significance of these data from **large** whales is not entirely clear, given that isotopic composition of zooplankton from some parts **of** the summer range **is** unknown. However, the data suggest that large whales tended to feed in different areas and/or on different **prey** types than **small** bowheads. Geographic segregation by size has been documented by photogrammetric studies on the summering grounds.
5. **The ratio** of the **stable** carbon isotopes (C-13/C-12) oscillated in a regular pattern **along** the lengths of baleen plates, with a spacing of **>25 cm/oscillation** **early** in **life**, and about 20 cm/oscillation in **adults**. During this study we determined **the** carbon isotope pattern **along the full** lengths of **baleen plates** from **11** different **bowheads**. **In large** whales, up to **20+** isotopic oscillations were present. **The** pattern of oscillations was consistent along two different plates from the same **whale**. The ratio was constant (within measurement limits) **at** different positions across the width of a **plate**.
6. The **C-13/C-12** oscillations along **the plates** were apparently annual, based on analyses of the radiocarbon (**C-14**) content of **baleen** from **two whales** killed in 1971 and 1966. **C-14** levels in the prey are believed to have increased around 1964 due to a peak in nuclear weapons tests. **C-14** levels at various points along the baleen increased **at** the expected positions, assuming a 1 yr cycle in stable isotope ratios. The stable isotope data themselves were also consistent with an **annual periodicity**. In whales killed during spring, the recently-formed **baleen** was enriched in C-13, **like** the **zooplankton** in the Bering Sea; **in** whales killed during fall, recently-formed **baleen** was relatively depleted of C-13.
7. **By** counting the stable isotope oscillations **along** the baleen, the ages of young bowheads can be determined. After several **years**, wear **at the tip of the baleen** makes age determinations imprecise, **but** a minimum age can **still** be determined. The **annual** isotopic oscillations also correspond with **visual** patterns **along** the baleen. **Thus**, it is now possible to estimate the age of a young bowhead based on **visual** inspection of its **baleen**, without isotopic analysis. **It** was not the purpose of this study to investigate **bowhead** growth rates, However, the data acquired incidental to our objectives showed that, after the age of about 1 year, **total** lengths of **bowhead** whales increase at a

slower rate **than** has been suggested previously. **For** example, bowheads **that** are 9 m **long** appear to be several years **old**.

8. The stable isotope patterns **in baleen** indicate that, after the first year or two of life, it grows from the upper jaw in **a** near-linear fashion. Since baleen is **'dead'** tissue once formed and is metabolically inactive, the carbon present at each point **along** a baleen **plate** is a sample of the carbon in the energy source in use by the **whale** when that part of the baleen was formed. Thus, the baleen provides a **multi-year** temporal record of feeding, representing **20+** years in **large** whales.
9. The C-13-depleted **'peaks'** in the **baleen** laid down in summer were consistent **with** the isotopic composition of **zooplankton in** the eastern **Beaufort** Sea. The C-13-enriched 'valleys' in the baleen **laid** down in winter were qualitatively consistent with the elevated C-13 content of **zooplankton** in the **western** Beaufort Sea and probably the northern Bering Sea. However, the degree of c-13 enrichment in **'winter'** baleen was greater than that expected based on the geographic shift in isotopic content of any one type of prey. It would appear that the 'winter' baleen must *incorporate carbon from* omnivores or secondary consumers, e.g. euphausiids or **amphipods**, in which **C-13** is further enriched. Our limited data on isotopic composition of zooplankton in the northern Bering *Sea* do not **allow** a reliable distinction of carbon from the western Beaufort Sea, **Chukchi** Sea and Bering Sea. Thus, it is not **possible** to say how much of the carbon in 'winter' baleen comes from feeding in the Bering Sea as opposed to mobilization of energy stored during **late** autumn feeding farther north.
10. The baleen of most young bowheads showed a decrease in overall **C-13** content in the first 6-8 years of **life**, accompanied **by increased** amplitudes of the seasonal oscillation in isotopic content.. The specific causes of these changes are uncertain. The transition from dependence on mother's **milk** to independent feeding may be partly responsible. Other possible factors are year to year **changes in** feeding *areas and/or a postulated* increase in the filtration efficiency of the lengthening baleen. Either factor could result in a shift in the diet toward smaller prey items like **copepods**, which are depleted of C-13.
11. In addition to the age-related trends noted above, there are other year **to** year changes in the **C-13/C-12** isotope ratios in bowhead baleen. Sometimes there is an unusually high or **low C-13** content in the baleen **laid** down in a single summer or **winter**. There can also be gradual trends (upward or downward) over a period of several years in the maximum **C-13** values achieved in winter. There seem to be parallel year **to** year trends **in** the isotopic composition of baleen from some different individual **bowheads**. Specific causes cannot be isolated at present, but these changes presumably represent changes in prey types, feeding areas, or primary production processes.

12. **Nitrogen isotope ratios (N-15/N-14) along the lengths of baleen plates** have **also** been determined for four bowheads. These **ratios** often undergo pronounced shifts, sometimes in apparent independence of shifts in carbon isotope ratios. The causes of **these** shifts are unknown. It **is** possible **that** occasional **N-15** enrichments reflect periods of fasting or **water** stress.
13. The results suggest that **small bowheads** acquire a significant amount of **energy** from feeding **in areas** west of the Eastern Alaskan **Beaufort** Sea. How much of this energy is acquired in winter in the **Bering** Sea **vs.** autumn or **spring in the western** Beaufort Sea or **Chukchi** Sea is unknown. The results from **large whales** are more difficult to **interpret**, but **they** may obtain the majority of their energy from somewhere other than the south-central and southeastern **Beaufort** Sea.
14. To resolve some of **these** uncertainties, **it** would be helpful to have **tissue** samples from additional bowheads harvested **in** spring and especially autumn. Tissue samples acquired in winter and summer **would** be very useful, but bowheads are not harvested at these times. It would **also** be very helpful **to** have data on isotopic ratios in **zooplankton** from deep waters of the eastern Beaufort Sea, and from the Amundsen **Gulf** area. (Presently available samples from the Canadian **Beaufort** Sea are **all** from continental **shelf** waters.) More **zooplankton** data from the northern **Bering** and **Chukchi** Seas are essential. Direct behavioral observations of **bowheads** in late **autumn**, **winter** and **early spring** might provide **confirmation** that they feed **in these** seasons. Isotopic analyses of **additional baleen** samples may **clarify** whether there are meaningful common patterns of isotopic variation in different individuals. Isotopic analyses of **baleen** will **also** provide **more** data on the age-length relationship, and will be **useful in assessing life history** and **reproductive** Parameters.





## ENERGETICS OF BOWHEADS\*

### Introduction

This section of the report relates **to the** third and **fourth objectives** of the **study**:

- **Estimate** the degree **of** utilization of available food resources in the **Eastern Alaskan Beaufort Sea** **by the** Western **Arctic bowhead whale stock**.
- Test the following **null** hypothesis:  
Food resources consumed **in** the Eastern Alaskan Beaufort Sea do not contribute significantly to the annual energy requirements of the Western Arctic bowhead whale stock.

**In** this section we estimate the food requirements of bowheads at the individual and population levels. These estimates are used in the subsequent 'Integration' section to estimate food utilization in the study area and to test the overall **null** hypothesis.

Large whales cannot be kept in captivity **and are** difficult to study in the **wild**, especially in the undisturbed **state**. Direct estimation of energetic requirements for these animals is, thus, difficult. **Lockyer (1981)** and **Thomson and Martin (1984)** estimated the feeding rates **of** Antarctic **rorquals** **and** gray whales, but. their **estimates** were based on circumstantial evidence **and** many assumptions. Gray **whales** are **benthic** feeders and **leave** a record of **their** feeding activities on the sea bottom; even with this evidence, it was possible to make only a rough estimate of food consumption. **Planktivorous** bowhead whales **leave no** such record and the estimates **of** their feeding rates developed here **also** involve many assumptions and much circumstantial evidence.

To **estimate the** feeding rates of bowheads, we must **estimate** (1) quantities of **zooplankton** near feeding whales, (2) size of the mouth opening **and** swimming speed while **feeding**, and (3) number of **hours** of feeding per day. These data **can** be used to **estimate daily** consumption of **zooplankton**.

As **a** check on and supplement to the estimates of food consumption made from **field** studies, this section also estimates the theoretical energy requirements of bowhead whales using five approaches, some of which are interrelated:

1. Respiration method: Energy requirements are estimated using observed breathing rates and estimated **lung** volumes **to** estimate oxygen consumption and thus metabolic rate. This approach is **an** adaptation of a method applied **to** Antarctic **rorquals** by **Lockyer (1981)** and to gray whales by **Sumich (1983)**.
2. Basal metabolism **is** estimated using **Kleiber's** equation for terrestrial mammals. This equation is also applicable **to** marine mammals (**Lavigne et al. 1986**).

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\* By Denis H. Thomson, LGL Ltd.

3. Standard metabolism is estimated using the method of **Brodie** (1975, 1981).
- 4\* Power output: An estimate of metabolic requirements is derived by estimating **muscle** power output using the assumptions of Lockyer (1981).
5. Cost of motion through the water is estimated using the hydrodynamic method of **Sumich** (1983), with improvements.

These five theoretical **estimates** are compared to one another and with **estimates** that have been derived for other whales. Based on the results of **this comparison**, we present estimates of energy needs for calves, **subadults**, **adult** males, and adult females. Energetic costs of growth, pregnancy and lactation are taken into account.

As background material for these analyses, it was necessary to estimate several aspects of the sizes of **bowheads**. In order to make a direct estimate of feeding rates, the cross-sectional area of the mouth opening while feeding must be known. The various theoretical estimates require data on body weight (for the **basal** metabolism method), weight of muscle (power output), **lung** volume (respiration method), metabolically active surface area (standard metabolism) and total surface area (hydrodynamic method). To estimate **the** amount of energy needed for growth, the proportion of muscle and blubber for animals of various sizes must **also** be known. Most of these data were not previously available for **bowhead** whales. "

This examination of **bowhead energetics** is an update of a similar section in an interim report (Thomson 1986). The present analysis takes account of recently acquired data of several types. Although the results are similar to those of Thomson (1986), the specific values reported here supersede those in the previous report.

#### Size of Bowhead Whales

##### Weight and Surface Area vs. Length

Direct measurements of the weights of **bowhead** whales are not available. Volumes, weights and surface areas of bowheads were estimated using measurements made from known-scale aerial photographs. Twenty one vertical photographs (19 different whales) taken in 1981-86 by Davis et al. (1982, 1983, 1986a,b) and during this study (see '**Bowheads**' section) showed good definition of both sides of the whale as **well as its** length. Techniques used to measure lengths of whales are described in Davis et al. (1983). The **whales** were assumed to be circular in cross section and were divided into five truncated cones. The length of each segment, its **diameter** at **each end**, and the **total length** of the whale image were measured (in mm) from the photographic prints. These measurements were compared to total **whale length** (in m) as determined **photogrammetrically** in order to obtain actual measurements of the 'segments' in meters. As a check on accuracy, the fluke width was estimated from the prints by the same method, and compared to previous **photogrammetric** measurements of the same parameter. The error in our measurements from prints as compared to the earlier **photogrammetric** results was 1.4%  $\pm$  s.d. 1.2%. This

imprecision is additional to inherent uncertainty in the photographic technique, which was about 3% (Davis et al. 1983).

The weights and surface areas of the 19 bowheads were estimated by summing the calculated volumes and surface areas of the truncated cones. Density was assumed to be 1 kg/L. The metabolically active surface area is the surface area of muscle (Brodie 1981). The region posterior to the blowhole was taken to be the body core, and the body core was assumed to be covered by 25 cm of blubber (15 cm in neonates; Lubbock 1937; Brodie 1981). The surface area and volume of the metabolically active body core were calculated from the outer dimensions of the truncated cones. The weight of blubber covering the entire body was also calculated assuming that blubber thickness on the head was the same as that on the rest of the body. The weight of muscle and viscera was calculated assuming a density of 1 kg/L.

The various estimates for 19 whales (Table 57) were plotted against whale length and curves were fitted by regression. Analysis of scatter plots and residuals indicated, as expected, that power curves (weight =  $A \text{ length}^B$ ) best described the length-weight relationships. The resultant equations were used to estimate these parameters for whales of various sizes.

The length-weight relationship of bowheads as derived above is similar to that of Pacific right whales and that of humpbacks (cf. Lockyer 1976). For a given length, bowheads are much heavier than the rorquals--fin, blue and sei whales (Fig. 165). Bowheads appear to be slightly heavier than right and humpback whales of equivalent length; however, different techniques were used to estimate the length-weight regressions of the different species, so caution is necessary in interpreting small differences.

The area of the tail fluke was calculated from known-scale photographs of 12 whales ranging in length from 4.9 to 16.2 m. These areas were also plotted against whale length and a curve was fitted by regression. A power curve best described this relationship:

$$\text{fluke area (m}^2\text{)} = 0.0135 \text{ length (m)}^{2.2}, r = 0.987$$

This equation was used to derive estimates of fluke areas for whales of various sizes.

#### Mouth Opening

In order to estimate potential feeding rates of bowheads, it is necessary to know the size of the mouth opening. The mouth area of a bowhead can be calculated from the length of the baleen, width of the head, and mouth gape.

The maximum length of baleen and whale length are available for 25 whales taken by the 'Cumbrian' in 1823 (Lubbock 1937), 6 whales measured by Scoresby (1820), 2 measured by Scammon (1874) and 11 whales reported on by Schell et al. (this report). These maximum baleen lengths were plotted against whale length and curves were fitted by regression. A linear regression best described this relationship:

Table 57. Estimates of weight, surface area, **weight of muscle and viscera**, metabolically active surface area, and weight of blubber for **bowhead** whales of various sizes. All data were estimated from aerial photographs as described in the text.

Length (m)	Weight (MT) <sup>a</sup>	Surface area (m <sup>2</sup> )	Weight of muscle and viscera (MT)	Metabolically active surface area (m <sup>2</sup> )	Weight of Blubber (MT)
<b>5.82</b>	<b>4.41</b>	<b>15.82</b>	2.12	9.23	2.38
<b>6.40</b>	6.97	<b>21.59</b>	3.93	<b>14.25</b>	<b>4.15</b>
11.57	<b>27.15</b>	56.80	10.86	28.12	14.96
11.24	23.95	52.81	9.48	26.73	12.73
<b>12.96<sup>b</sup></b>	36.70	70.34	15.97	38.21	<b>21.40</b>
<b>12.96<sup>b</sup></b>	37.05	70.08	<b>16.10</b>	37.76	21.81
9.83	16.90	41.98	6.39	20.84	8.18
<b>11.25</b>	24.16	51.76	9.36	25.17	13.14
13.97	44.15	79.48	19.06	41.21	26.71
<b>14.36</b>	49* 03	<b>84.11</b>	22.60	<b>45.81</b>	30.43
14.68	53.10	90.01	25.90	51.69	<b>33.16</b>
10.00	<b>21.60</b>	47.24	8.43	23.41	<b>11.55</b>
<b>11.99</b>	35.98	68*00	<b>16.17</b>	37.11	<b>21.15</b>
<b>12.90</b>	<b>45.77</b>	77.59	<b>21.94</b>	43.75	28.63
<b>14.27<sup>b</sup></b>	57.79	92.60	<b>25.78</b>	48.83	<b>37.12</b>
<b>14.27<sup>b</sup></b>	60.85	95.19	28.83	52.50	39.56
<b>13.21</b>	44.78	79.50	<b>20.56</b>	42.72	27.28
13.57	45.36	80.11	19.81	42.23	27.72
13.70	44.47	79.23	<b>18.53</b>	39.36	27.04
9.65	<b>15.74</b>	39.35	5.54	<b>18.30</b>	7.58
<b>12.54</b>	<b>39.41</b>	<b>71.18</b>	<b>16.64</b>	36.53	23.80
Regression equation <sup>c</sup>					
A	<b>0.0417</b>	<b>0.6337</b>	0.0214	0.4349	<b>0.0312</b>
B	2.675	1.851	2.606	1.745	2.437
r	<b>0.99</b>	0.99	0.96	0.97	0.99

<sup>a</sup> MT = Metric tons (1 MT = 1000 kg).

<sup>b</sup> Replicate photographs of the same whale.

<sup>c</sup>  $Y = A(\text{length})^B$ , where y = weight, surface area, etc. Does not include replicates, for which an average value was used.

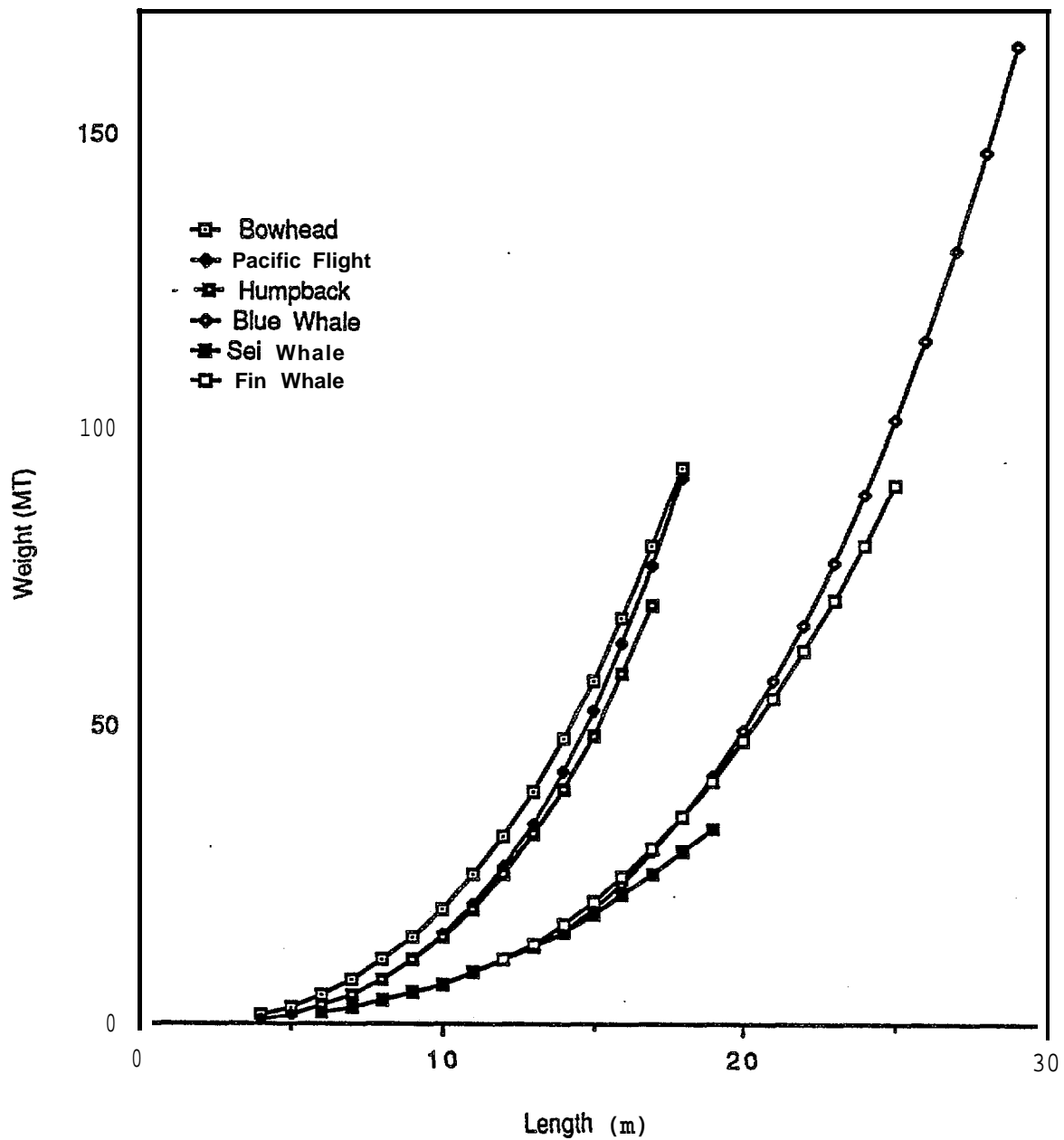


FIGURE 165. Body weight at length in blue, fin, sei, humpback and right whales (Lockyer 1976) and bowhead whales (this study).

$$\text{Baleen length (cm)} = -70.8 + 0.25 \text{ whale length (cm)}, r = 0.94$$

The width of the head near the blowhole, as measured on **aerial** photographs, is  $19.3\% \pm \text{s.d. } 1.4\%$  of body length ( $n = 19$ ), and **at** this point the width of the upper jaw is **about** half that of **the** lower jaw. Maximum body width posterior **to the head** occurs at the position of the flippers, and is  $22.7\% \pm \text{s.d. } 1.9\%$  of body length. The mouth is narrow at the anterior end and becomes progressively wider toward **the** back. **At** the corners of the mouth, width would be between the aforementioned  $19.3\%$  and  $22.7\%$  of body length values. The **baleen** is short at the anterior end and becomes longer. farther back. The cross-sectional area of the mouth **opening** through **which** water would enter the mouth **is** variable and can be **controlled** by opening and closing the jaws.

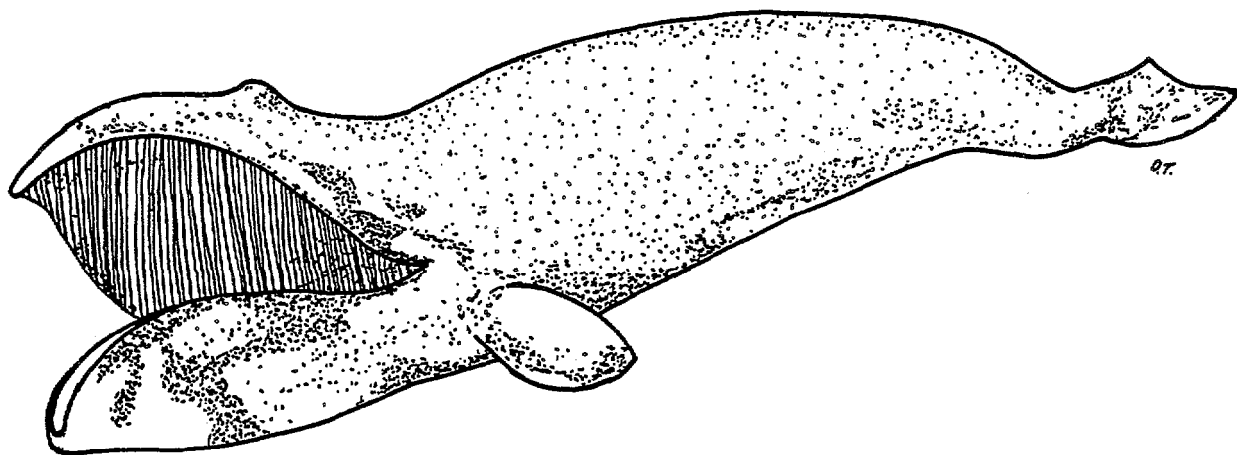
Aerial photographs (Fig. 166) and observations of whales by ourselves and others (e.g., **Scoresby** 1820; **Würsig et al.** 1985a) show that, at **least** when surface feeding, the mouth opening may be quite large. Similarly, right whales have been observed and photographed feeding near **the** surface with their **mouths** open widely (**Watkins and Schevill** 1976, 1982). The short anterior baleen plates apparently do not touch **the lower** jaw during feeding. The most anterior baleen that is in contact with the **lower** lip is near the blowhole (Fig. 166). While feeding, the lower **lips** expand laterally and the baleen **plates** are spread to contact the **lower** lip. When the mouth is open wide **while** feeding, the upwardly-arching lower lip maintains the plankton trap effect even when the **anterior** baleen **is not in contact with the bottom** of the mouth. Since the mouth becomes wider posteriorly, the effective cross-sectional area of the opening becomes much larger as the mouth is opened wider.

The above observations are of bowheads (and right whales) feeding within a meter or two of the surface--close enough to the surface to be visible from an aircraft. We have no information **on** the size of the-mouth opening when bowheads feed farther **below the** surface, where most feeding occurs,. However, some of our observations of near-surface feeding involved whales swimming below the surface with mouths wide **open**. For the purposes of energetic computations, we assume that they feed in the same way when feeding deeper in the water. The jaws are assumed to be open far enough that **the** most anterior baleen to contact the lower jaw is near the blowhole.

The cross-sectional area of the mouth opening was calculated as follows. The mouth opening at the point where the baleen intersects the lower lip was assumed to be the width of the unexpanded lower jaw near the blowhole ( $19.3\%$  of body length). The upper jaw was estimated to be one-half this width ( $9.65\%$  of body length). The length of the longest baleen was calculated from the above equation. The width of the upper jaw was then reduced by one-third to allow for the lips and width of the baleen. The tongue was assumed to occupy one-third of the oral cavity when the mouth was open. Based on these data and assumptions the cross-sectional area of the mouth opening for whales 7 to 18 **m long can be** approximated by the equation

$$\text{Mouth opening in m}^2 = 0.00948 \times (\text{total length in m})^{2.365}$$

A 14.5 m adult would have a mouth opening of 5.3 m<sup>2</sup>; **corresponding** values for 8, 13.7 and 16 m whales would be 1.3, 4.6 and 6.7 m<sup>2</sup>, respectively.



**FIGURE 166.** Outline of a photograph of an 8.6 m bowhead whale that was skim feeding on its side near the water surface. The photograph was taken from an aircraft off the Yukon coast in the Canadian Beaufort Sea on 30 August 1985 by Davis et al. (1986b).

A wide variety of estimates of mouth opening have been reported previously for right and bowhead whales. Nemoto (1970) estimated the mouth opening of a right whale to be  $8.9 \text{ m}^2$ . It should be noted that the head of a right whale is proportionately smaller than that of a bowhead. In contrast, Kenney et al. (1986) calculated that an average right whale had a  $1.1 \text{ m}^2$  mouth opening. This estimate is based on Watkins and Schevill's (1976) observations of mouth size, and assumes that when feeding the short front baleen plates are in contact with the lower lip. However, Watkins and Schevill (1976, 1982) also found that, when right whales are surface feeding, the mouth is sometimes wide open and the tongue is visible forward of the long places. Kenney et al.'s estimate is, therefore, a minimum one. Brodie (1981) assumed that the mouth opening of a 13.7 m bowhead was only  $1 \text{ m}^2$ , as compared with our estimate of  $4.6 \text{ m}^2$  for a whale of this size. Brodie did not provide details of how the  $1 \text{ m}^2$  figure was calculated. Griffiths and Buchanan (1982) considered both Nemoto's  $8.9 \text{ m}^2$  and Brodie's  $1 \text{ m}^2$  figures in their analyses of bowhead energetic, plus an intermediate  $5.0 \text{ m}^2$  value. Lowry and Frost (1984) estimated that the mouth opening of a 13.7 m bowhead was  $3.6 \text{ m}^2$ . Their value is apparently too low because they underestimated length of baleen and width of upper and lower jaw.

#### Size Structure of Population

To estimate the energetic requirements of the whale population, it is necessary to know the number of animals of each size. Davis et al. (1983, 1986a,b), Cubbage et al. (1984) and Cubbage and Calambokodis (1987a,b) measured "the lengths of many bowhead whales in the Canadian Beaufort Sea in 1982-86. However, these data are not necessarily representative of the length-frequency distribution of the population as a whole because animals

were segregated by size, especially in 1983-86. This 'size segregation was less apparent in 1982. **Photogrammetric** studies of the size distribution of the population during spring migration near Barrow may **yield** a **less** biased estimate (Nerini et al. 1987). In the spring of 1985 most of the spring migration period was **sampled, and the size structure** of the population (exclusive of calves) was similar to that found in the summer of **1982** by Davis et al. (1983, p. 42, 79).

Given this **similarity**, we have followed our previous practice (e.g. Thomson 1986) of **using** the 1982 data to estimate the length-frequency **distribution** of the population for the purposes of energetic computations (Table 58). The mean lengths of calves in summer, **subadults**, and **adults** were calculated from the length-frequency distribution of Davis et al. (1983). The **mean weight** of individuals in each **category was not** assumed to be the weight of a mean-length individual; that procedure tends to underestimate mean weight (Bird and Prairie 1985). Instead, the weight of each individual whale represented in the length-frequency distribution was calculated, and then the average weight for each category of whale was calculated (Table 58).

#### Estimated Dimensions and Weights for Average Individuals

The previously derived surface area and mouth area estimates were applied to various components of the population to determine parameters required in energetic computations (Table 58). Mean weights are the means for all individuals within each **category**, calculated as described above. Other parameters were, calculated on the **basis** of the length of a mean **weight individual**.

In the North Pacific right whale, blubber is 43% of body weight (Lockyer 1976). C. George (North **Slope** Borough, Barrow, AK, pers. **comm.**), through weighing a butchered "whale, estimated blubber to be 44% of body weight in an 11 m **bowhead**. **Scoresby** (1820) estimated that blubber was 43% of body **weight** in an 18.3 m bowhead. Using the **photogrammetric** data and assumptions about blubber thickness, we estimated that blubber is 40% of body weight in adult bowheads (Tables 57, 58). Lockyer estimated that the bone weight of North Pacific right whales is 13% of body weight, and that the weight of viscera is **also 13%** of body weight. We assume that these **values apply** to bowheads.

#### Theoretical Energetic Requirements

Theoretical energetic requirements **can** be estimated in a variety of ways. The respiration method **yields** an **estimate** of **active metabolism**. If **respiration** rates are measured over a wide range of **activities, as has been** done for bowheads, then this estimate may be representative of average active metabolism. In contrast, the power output and hydrodynamic methods **yield** estimates **for a specific activity--motion**. These methods were used for comparison with the results of the respiration method as applied to migrating whales. The **basal** metabolism method represents the minimum expected rate of energy expenditure, and applies to resting animals. **It** is useful for comparison with active rates. The standard metabolism method **yields an** estimate that includes basal metabolism and other metabolic costs such as warming ingested food and inspired air. All of these methods are compared in



**Table 58.** Estimated dimensions and weights of average bowheads. Mean lengths and weights are the means of all individuals within the indicated category. The remaining calculations are based on length of a mean-weight individual within that category. Relative abundances of various categories of bowhead whales are based on data of Davis et al. (1983).

	Calves	Subadults	Adults	Average Non-Calf
Size range (m)	4.1-7.6	7.6-13	13-18	7.6-18
% of population	10.6	52.3	37.2	89.5
Mean length (m)	6.45	10.8	14.5	12.4
Mean weight (MT)	6.2	24.9	53*7	37.7
Length at mean weight (m) <sup>a</sup>	6.5	10.91	14.55	12.75
Body surface area <sup>a</sup> (m <sup>2</sup> ) <sup>b</sup>	20	53	90	71
Total tail fluke surface area (m <sup>2</sup> )	1.7	5.2	9.8	7.3
Weight of muscle and viscera (MT) <sup>c</sup>	2.8	11	23	16
Metabolically active surface area (m <sup>2</sup> )	11	28	46,	37
Weight of blubber (MT)	3.0	10.5	21.3	15.4
Mouth opening (m <sup>2</sup> )	? <sup>d</sup>	2.7	5.3	3.9

<sup>a</sup> Mean weight is not the same as weight of a mean-length individual--see text.

<sup>b</sup> Not including tail flukes.

<sup>c</sup> Includes bones.

<sup>d</sup> Baleen is proportionately shorter in calves than adults.

this section. The respiration method, which covers a wider range of activities than the others, is used in later sections to estimate energetic requirements of various segments of the population and the population as a whole.

#### Respiration Method

Energy requirements can be estimated by calculating oxygen consumption of the animals (Sumich 1983). Estimates of oxygen consumption are based on the observed breathing rate plus estimates of the size of the lungs, tidal volume, and oxygen utilization.

Blow Rates .--Available data on blow rates (i.e. breathing rates) of **bowhead whales** in the eastern and western arctic are summarized in **Table 59**. The mean blow rates ranged from 0.43 to 1.01 blows/rein in various circumstances. Blow rates for **fall** migrating whales in the eastern and western arctic were about 0.61 and 0.73 blows/rein. Blow rates for feeding whales were about 0.52 to 0.92 blows/rein. The highest mean blow rate was for socializing whales; the lowest was for calves in summer and spring migrants in the Alaskan **Beaufort Sea** (Table 59). Mean blow rate for all activities in summer was 0.77 blows/rein (**Würsig et al. 1985b**). Mean blow rate for all activities during **fall** migration was 0.66 blows/rein according to **Ljungblad et al. (1984b)** and 0.70 blows/rein according to this study (Table 59). The weighted average of the two 'fall' values is 0.68 blows/rein.

It should be noted that these data were collected by different groups of observers using varying techniques. Calculated blow rates depend strongly on the mean dive times, and dive time data are often biased by observational problems. Thus, the mean values in Table 59 should be considered to be approximate, and apparent differences--particularly between results from different observation teams--should be treated with caution.

Swimming Speeds .--Data on migration speeds of bowheads are a useful indicator of the animal's level of activity. Traveling speeds of bowhead whales have been measured in several areas. During fall migration in **Baffin Bay**, **Koski and Davis (1980)** used a cliff-based theodolite to measure the traveling speeds of 22 southbound whales as  $5.01 \pm \text{se. } 0.28$  km/h. The speeds of 10 other whales recorded over an average distance of 14.3 km using aerial and cliff-based observations was  $4.7 \pm \text{se. } 0.5$  km/h. **Ljungblad et al. (1984b)**, based on aerial observations, estimated swimming speeds of migrants during the autumn migration through the Alaskan Beaufort Sea. Five individual whales averaged  $5.0 \pm \text{s.d. } 1.97$  km/h and two groups of approximately 10 whales each averaged 4.3 and 8.5 km/h. Mean speed of all animals observed by **Ljungblad et al. (1984b)** was 6.1 km/h.

Off Cape Lisburne in the **Chukchi Sea**, **Rugh and Cabbage (1980)** estimated that northbound spring migrants averaged  $4.7 \pm \text{s.d. } 0.6$  km/h. During spring migration at Barrow, **George and Carroll (1987)** found that swimming speeds of cow/calf pairs adjusted for current were  $4.2 \pm \text{s.d. } 1.1$  km/h ( $n = 18$ ). **Rugh (1987)**, using a photographic refighting technique, measured mean speeds of 5.1 km/h to 1.2 km/h for spring whales migrating past Barrow. The slower mean speeds were for resightings made >10 h apart.

Fewer data are available on speeds of feeding whales. **Würsig et al. (1982)**, based on theodolite data from **Herschel Island** in 1980, found an average speed at the surface of  $5.1 \pm \text{s.d. } 2.93$  km/h ( $n = 18$ ) for whales that appeared to be feeding while below the surface. **Finley et al. (1986)**, also using a theodolite, measured swimming speeds of bowheads feeding in deeper water near **Baffin Island**. Whales feeding at a specific location showed little horizontal movement from one surfacing to the next. It is not known how far or fast they travelled while under water. A whale feeding near the surface along a windrow visible at the surface travelled at 2.1 to 5.2 km/h over the 5 h that it was tracked. Rate of movement slowed and dive duration increased where the windrow was most prominent (**Finley et al. 1986**).

**Table 59.** Surfacing, respiration and **dive characteristics** for presumably undisturbed **bowhead whales** from the eastern and western arctic. Mean  $\pm$  standard deviation (sample size) are given.

	Duration of Dive (min)	Duration of Surfacing (min)	Blow Interval (s)	Number of Blows per Surfacing	Number of Blows per Minute <sup>a</sup>	Reference
<b>Alaskan Beaufort Sea, Fall</b>						
Travelling whales	6.01 $\pm$ 5.19 (31) 8.76 $\pm$ 11.70 (2)	1.48 $\pm$ 0.87 (75) 1.41 $\pm$ 0.79 (8)	16.7 $\pm$ 9.15 (611) 12.7 $\pm$ 3.55 (123)	5.5 $\pm$ 3.12 (73) 6.7 $\pm$ 4.08 (6)	0.73 0.66	Ljungblad et al. (1984b) This study (Table 49)
Water Column feeding	8.78 $\pm$ 6.60 (26) 6.46 $\pm$ 8.31 (10)	1.01 $\pm$ 0.62 (82) 1.25 $\pm$ 0.84 (2)	11.7 $\pm$ 6.23 (582) 12.8 $\pm$ 6.18 (350)	5.4 $\pm$ 3.26 (75) 4.9 $\pm$ 3.30 (17)	0.55 0.64	Ljungblad et al. (1984b) This study (Table 49)
Mothers with calves	8.63 $\pm$ 4.26 (8) 12.29 $\pm$ 6.15 (7)	2.11 $\pm$ 1.02 (11) 1.63 $\pm$ 0.65 (29)	17.6 $\pm$ 6.49 (87) 12.8 $\pm$ 5.80 (515)	7.2 $\pm$ 4.38 (11) 6.8 $\pm$ 2.73 (18)	0.67 0.49	Ljungblad et al. (1984b) This study (Table 48)
Calves	8.57 $\pm$ 4.13 (8) 10.78 $\pm$ 6.23 (3)	2.10 $\pm$ 1.08 (12) 1.92 $\pm$ 1.31 (4)	15.05 $\pm$ 14.69 (104) 15.6 $\pm$ 10.49 (111)	8.5 $\pm$ 4.25 (11) 5.67 $\pm$ 4.16 (3)	0.80 0.45	Ljungblad et al. (1984b) This study (Table 48)
All non-calves, all activities	7.11 $\pm$ 5.94 (59) 6.46 $\pm$ 7.75 (28)	1.33 $\pm$ 1.10 (168) 1.17 $\pm$ 0.73 (114)	14.4 $\pm$ 9.46 (1261) 11.55 $\pm$ 5.28 (1295)	5.6 $\pm$ 3.34 (154) 5.36 $\pm$ 3.64 (68)	0.66 0.70	Ljungblad et al. (1984b) This study (Table 48)
<b>Baffin Island, Fall Migration</b>						
Travelling at 4.7 to 5 km/h	8.65 $\pm$ 2.73 (88)	1.69 $\pm$ 1.01 (93)	16.1 $\pm$ 8.29 (399)	Approx. 6.3	0.61	Koski and Davis 1980)
<b>Northwest Alaska, Spring Migration 1980-1985</b>						
Travelling	11.72 $\pm$ 5.30 (156)	1.59 $\pm$ 0.47 (19)	13.7 $\pm$ 3.69 (MO)	6.5 $\pm$ 2.64 (78)	0.49	Carroll et al. (1987)
Feeding	14.70 $\pm$ 6.51 (16)	2.32 $\pm$ 0.60 (39)	11.9 $\pm$ 4.06 (361)	12.6 $\pm$ 2.20 (37)	0.74	"
<b>Southeastern Beaufort Sea, Summer 1980-1986</b>						
Calves	4.96 $\pm$ 5.36 (45)	1.05 $\pm$ 1.13 (51)	16.0 $\pm$ 13.58 (178)	2.6 $\pm$ 2.45 (41)	0.43	Wirsig et al. (1985b)
Adults with calves	8.17 $\pm$ 6.49 (39)	1.74 $\pm$ 1.39 (47)	16.9 $\pm$ 8.27 (325)	5.1 $\pm$ 4.16 (33)	0.52	"
Non-calves (not including above)	3.92 $\pm$ 6.14 (294)	1.15 $\pm$ 1.11 (668)	13.3 $\pm$ 8.83 (48%)	4.3 $\pm$ 3.19 (8)	0.85	"
Skim-feeding whales	1.80 $\pm$ 2.84 (25)	3.19 $\pm$ 3.55 (27)	25.3 $\pm$ 21.58 (198)	4.6 $\pm$ 3.63 (23)	0.92	"
Bottom feeding whales	6.36 $\pm$ 10.85 (4)	1.21 $\pm$ 0.67 (12)	11.9 $\pm$ 5.12 (139)	5-8 $\pm$ 3.61 (10)	0.77	"
Actively socializing whales	2.66 $\pm$ 3.14 (32)	1.22 $\pm$ 0.77 (76)	14.2 $\pm$ 9.93 (553)	3.9 $\pm$ 2.23 (61)	1.01	"
All non-calves, all activities	4.42 $\pm$ 6.32 (333)	1.19 $\pm$ 1.14 (715)	13.5 $\pm$ 8.88 (5161)	4.3 $\pm$ 3.25 (626)	0.77	"

<sup>a</sup> Mean blows per surfacing / (Mean duration of dive + mean duration of w-facing). Values calculated in this way & not always agree with blow rate values reported in the cited reports.

During the present study, several observations were made of distance travelled and dive duration for whales that were apparently feeding (see 'Bowheads' section, p. 353). Mean swimming speed for submerged whales that were apparently feeding was 1.2 km/h. This minimum estimate includes only the straight-line horizontal distance from dive to surfacing (mean of about 337 m in 17.3 min,  $n = 17$ ), and does not include vertical distance or curves in the underwater paths of the whales.

Lung and Heart Size--- Henry et al. (1983) measured the dimensions of one preserved lung from each of five bowhead whales. Volumes that we calculated from their measurements were used to estimate the **total** volume of the preserved and collapsed lungs. **Only** one lung was actually weighed. The **left lung** of an 8.7 m whale weighed 33.2 kg. The collapsed right lung was not weighed, but had a **volume** of 30.5 L. Based on this, we assumed that collapsed **lung volume** (in L) is a close approximation of the weight (in kg), i.e. that the density of the preserved and collapsed lungs was 1 kg/L (Table 60).

The estimated weights of bowhead lungs (as calculated from volume) are far smaller than those found in other whales. For minke, right, sei, fin and blue whales, **lung** weight is 0.65 to 0.85% (mean 0.76%) of body weight (Lockyer 1981; Lockyer and Waters 1986). In blue and fin whales, **total** lung capacity in liters is 2.5 to 2.8% of body weight in kg (Lockyer 1981). If we assume that **total lung capacity is proportional** to lung **weight**, which is **lower in** bowheads than in other **baleen** whales, then **total** lung capacity for bowhead whales (in L) would be about 1.5% of body weight (in kg).

Table 60. Lung size of five bowhead whales, based on measurements by Henry et al. (1983).

Measured Length of Whale (m)	Estimated Weight of Whale <sup>a</sup> (MT)	Measured Dimensions of Collapsed Lung (cm) <sup>c</sup>	Estimated Weight of Lungs <sup>c</sup> (kg)	Estimated Lung Weight as a% of Total Weight
10.9	24.8	12 x 72 x 42	73 (L) <sup>d</sup>	0.29
10.8	24.2	13 x 77 x 50	100 (R)	0.41
10.0	19.7	13 x 77 x 41	82 (L)	0.42
8.7	13.6	12 x 72 x 36	62 (R)	0.46
8.7	13.6	11 x 87 x 42	80 (R)	0.59
Mean $\pm$ s.d				0.43 * 0.10

<sup>a</sup> Estimated from equation in Table 57.

<sup>b</sup> Thickness x mean length x mean width.

<sup>c</sup> Estimated from calculated volume assuming tissue density of 1 kg/L.

<sup>d</sup> L = left, R = right--indicates which lung was used for the estimate.

The small lung size of bowhead whales may also be reflected in small heart size. Only a portion of one heart has been weighed. Seventy-five percent of the heart of a 12.7 m whale was reported to weigh 80 kg (Jones and Tarpley 1981). The entire weight would have been roughly 107 kg. A 12.7 m whale would weigh about 37 MT. According to Lockyer (1981), heart weight of a whale is approximated by the equation Heart weight =  $0.00588 \text{ Body weight}^{0.984}$ . Thus, for a 37 MT whale, the heart is expected to weigh about 184 kg. Thus, based on the meager available evidence, bowhead heart weight ( $n = 2$ !) is about 58% of predicted weight, and the lungs ( $n = 5$ ) are about 54% of the weight of those of other whales of comparable size. It should be noted that heart and lung sizes of bowheads would be more comparable to those of other whales if we are overestimating total body weight of bowheads (cf. p. 441).

In whales, the volume of inspired air or 'vital capacity' is about 80% of the total lung capacity; about 10% of the inspired air is utilized as oxygen. We use these values, although we realize that breaths during some activities and situations may provide more oxygen than other breaths.

Estimation of Energetic Requirements Through Respiration.--Energetic requirements of bowhead whales were calculated as follows: The blow rates for migrating and feeding animals are available for non-calves in general, not by whale size, so the computations were made for an average non-calf bowhead weighing about 37.7 MT (Table 58). The previously discussed estimates of lung weight, lung capacity, tidal volume and oxygen utilization were used to estimate the amount of oxygen consumed per blow. The blow rates during various activities were then used to compute daily oxygen consumption, which was then converted to energy utilization in Kcal (1 L of  $O_2$  consumed corresponds to 4.75 Kcal, Sumich 1983). In the southeastern Beaufort Sea in summer, mean blow rate for all non-calves (all activities combined) was 0.77 blows/rein (Table 59). Energy expended for an average bowhead respiring at this rate is  $2.4 \times 10^5$  Kcal/d (Table 61). Feeding is the main activity of whales in the southeastern Beaufort Sea, so this estimate is heavily weighted to feeding activities (Würsig et al. 1985a,b).

#### Other Theoretical Estimates

Basal Metabolism.--The basal metabolic rate is the metabolic rate measured at a metabolically indifferent temperature at rest or without abnormal activity (Kleiber 1961). It can be calculated from Kleiber's formula :

$$BMR = 70.5 W^{0.7325}$$

W is the weight in kg and BMR is the basal metabolic rate in Kcal/d. This formula was derived from measurements of the metabolism of resting terrestrial mammals, but it is also applicable to marine mammals (Lavigne et al. 1986). Based on this formula, basal metabolic rates for bowhead whales of various sizes are shown below:

	<u>Neonates</u>	<u>Subadults</u>	<u>Adults</u>	<u>Average non-calf</u>
Weight (MT)	6.2	24.9	53.7	37.7
BMR, Kcal/d $\times 10^5$	0.42	1.17	2.06	1.59

For an average bowhead of weight 37.7 MT, basal metabolism would be  $1.6 \times 10^5$  Kcal/d. This is about 70%-84% of the estimated energetic requirement of an actively migrating whale, which is  $1.9\text{--}2.3 \times 10^5$  Kcal/d (Table 61).

Standard Metabolism.--This rate includes basal rate plus the cost of maintaining buoyancy and warming the air and food (Brodie 1975, 1981). Using Brodie's (1981) method, for an average bowhead of weight 37.7-MT and with a metabolically active surface area of  $37 \text{ m}^2$  (Table 58), heat production at the muscle surface would be about  $0.39 \times 10^5$  Kcal/d. Cost of warming air would be  $0.06 \times 10^5$  Kcal/d and cost of warming food about  $0.28 \times 10^5$  Kcal/d (see Brodie 1981). According to Brodie's method, standard metabolism (including basal metabolism) would be about  $0.7 \times 10^5$  Kcal/d, or only about half the estimate of basal metabolism computed above from Kleiber's equation. However, Brodie (1981) suggests doubling the estimate of standard metabolic rate to estimate typical daily energetic cost of all activities. The resulting  $1.4 \times 10^5$  figure for active metabolism would still be less than basal metabolism as estimated from Kleiber's equation.

Power Output.--In Antarctic rorquals engaged in feeding and other activities at speeds of 5.5 km/h, Lockyer (1981) estimates that power output is about 0.0001 hp/lb ( $1.64 \times 10^6$  ergs/s/kg). This power output is equivalent

Table 61. Estimated energetic requirements of an average (37.7 MT) bowhead whale engaged in socializing, feeding and migration, as computed from estimated oxygen consumption. Blows/rein data are from Table 59.

Weight (kg)		37,700
Lung volume in L (1.5% of weight in kg)		566
<b>Vital</b> capacity in L (80% <b>of</b> lung volume).		453
Oxygen utilization in L/blow ( <b>10%</b> of vital capacity)		45

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<u>Southeastern Beaufort Sea</u>	<u>Blows/min</u>	<u>Kcal/d</u>
Summer, all non-calves, all activities	0.77	2.4 x 10 <sup>5</sup>
Socializing whales	1.01	3.1 x 10 <sup>5</sup>
Skim feeding	0.92	2.8 x 10 <sup>5</sup>
<u>Alaskan Beaufort Sea.</u>		
All activities, all areas <sup>a</sup>	0.68	2.1 x 10 <sup>5</sup>
Water column feeding <sup>s</sup>	0.58	1.8 x 10 <sup>5</sup>
Migrating <sup>a</sup>	0.73	2.3 x 10 <sup>5</sup>
<u>Baffin Bay</u>		
Migrating at 5 km/h	0.61	1.9 x 10 <sup>5</sup>

<sup>a</sup> Weighted average (Ljungblad et al. 1984b and this study; see Table 59).

to 3.39 Kcal/d/kg of muscle. Only one-half the muscle is used at any one time (Lockyer 1981). Our average 37.7 MT whale contains about 16,200 kg of muscle, viscera and bones posterior to the blowhole (Table 58). If we allow 3.55 MT for organs and 3.55 MT for bones (see 'Size of Bowhead Whales' subsection), then the musculature operative at any one time is about half of 9100 kg, i.e. 4550 kg. During this level of activity about  $0.15 \times 10^5$  Kcal/d would be required in excess of basal metabolism (4550 kg x 3.39 Kcal/d/kg).

Hydrodynamic Cost of Motion. --The cost of motion through the water can be computed through hydrodynamic considerations. The cost of transport is

$$P = 0.5 \cdot \rho \cdot C_t \cdot S_w \cdot V^3$$

where P = power requirements in dyne.cm/s,  $\rho$  = density of water in g/cm<sup>3</sup>,  $S_w$  = surface area (cm<sup>2</sup>), V = swimming speed (cm/s) and  $C_t$  = coefficient of drag (Sumich 1983).

Sumich (1983) computed a coefficient of drag of 0.06 for a 15 MT gray whale migrating at about 7 km/h. The estimate was based on breathing rates and lung capacity. He extrapolated lung volume of a young gray whale to the adult, assuming that tidal volume in L = 3.5% body weight in kg. However, in the gray whale, lung capacity as a percentage of body weight appears to decrease with increasing size. In the gray whale fetus, total lung weight is 2.5% of total body weight (Blokhin 1984). Lung weight in a 31,460 kg (not including blood) female was 333 kg (Yablokov and Bogoslovskaya 1984). Adding 6% to the body weight for blood loss (Lockyer 1981), the lung weight of this adult was 0.99% of body weight. Most other species of whales also have a lung weight about 1% of body weight, and a total lung capacity (in L) of 2.5 to 2.8% of body weight in kg (Lockyer 1981). Vital capacity is about 80% of total lung capacity. Based on the higher figure for total lung capacity (2.8%) and a tidal volume of 80%, tidal volume in L = 2.2% of body weight in kg. Based on this 2.2% figure and the cost of transport equation given above, cost of transport for a gray whale would be 0.068 Kcal/kg/km and the drag coefficient would be 0.04.

The above calculations of cost of transport and drag coefficient for a gray whale are based on an energy utilization figure that includes basal metabolism. Excluding basal metabolism, the coefficient of drag for a gray whale is 0.02 and cost of transport is 0.036 Kcal/kg/km. This drag coefficient will be used to approximate the drag coefficient of a bowhead. It takes into account only the power, over and above basal metabolism, required to move the animal through the water.

For an average bowhead whale moving at 5 km/h (139 cm/s) and with total surface area, including the flukes, of  $7.8 \times 10^5$  cm<sup>2</sup> (Table 58), cost of transport would be  $2.2 \times 10^{10}$  dyne.cm/s, or about  $0.43 \times 10^5$  Kcal/d. Basal metabolism for this animal was computed to be  $1.6 \times 10^5$  Kcal/d, so total energy requirements at this speed would be  $2.0 \times 10^5$  Kcal/d.

#### Comparison of Estimates for Bowheads and Other Whales

Several different methods have been used to compute the energetic requirements of an average non-calf bowhead whale. With the exception of the standard metabolism estimate (based on the method of Brodie 1975, 1981), the estimates are similar to one another:

	$\times 10^5 \text{ Kcal/d}$
Breathing rates - migration (5 km/h)	1.9-2.3
- summer average	2.4
Basal Metabolism	1.6
Power output (5 km/h)	0.15 + BMR = 1.75
Hydrodynamic (5 km/h)	0.4 + BMR = 2.0
Standard metabolism	0.7

The energetic requirements of traveling, as computed from power output and hydrodynamic considerations, are close to one another and at the low end of the range of values computed from breathing rates. Active metabolism while traveling is estimated to be about 9 to 44% in excess of basal metabolism, depending on **the** method used to estimate active metabolism (power output, hydrodynamic, respiration). Based on the respiration method, the summer average **value** of  $2.4 \times 10^5 \text{ Kcal/d}$  for **all activities** in the **southeastern** Beaufort Sea is similar to the  $2.2 \times 10^5 \text{ Kcal/d}$  estimated for all activities in **the** present study area (**Table 61**). These estimates represent an energy expenditure 38% to 50% in excess, of estimated **basal** metabolism.

The standard metabolism estimate is **meant** to include basal metabolism (**Brodie 1981**) but it is less than half the basal metabolic rate estimated from **Kleiber's** equation. Using empirical evidence, **Lavigne et al. (1986)** found that basal energetic requirements of marine mammals are well described by **Kleiber's** equation. The metabolic requirements of whales estimated by several different methods, including measured feeding rates in the wild and in captivity, are not consistent with the **low** metabolic rate predicted from **Brodie's** standard metabolism method (**Hinga 1979; Lockyer 1981; Thomson and Martin 1984; Lavigne et al. 1986**). The **estimate** derived from standard metabolism is not considered further in this report.

Active **bowheads** may have **lower** energy requirements than expected for whales of their size (**Table 62**). The active rate may be only about 40 to 50% above the basal rate. The active metabolic rates for gray whales (food removal method), blue whales, and fin whales have been estimated "to be two to three times the basal metabolic rate (**Table 62**).. Marine mammals in general have **average** active metabolic rates that are about double the basal rates (**Lavigne et al. 1986**). However, **Hinga (1979)**, like <sup>us</sup>, found evidence that **large whales** have average **annual** metabolic rates that are only about 1.5 times the basal rate. Recent results from **Brodie and Paasche (1985)** are also consistent with the idea that active metabolic rates of large whales **are** low. **Brodie and Paasche** found **that** the body core temperatures of large whales were lower than those of other mammals, and there was a gradient of decreasing temperature from the core to the muscle/blubber interface. They also found that body temperature did not rise after exertion (pursuit), and they speculate that **whales** are **very** hydrodynamically and **biomechanically** efficient. Thus, available data for large whales indicate that active metabolism is about 1.5 to 3 times basal metabolism, with **recent work** supporting **the lower ratio**.



Table 62. Estimated metabolic rates of large whales.

Species and activity(method)	Weight (kg)	Metabolic rate Kcal/kg/d	Reference
Bowhead - basal metabolism <sup>a</sup>	35,000	4.3	This study
-migrating 5 km/h (various)	35,000	5.0 to 5.8	This study
-average sinner (respiration)	35,000	6.4	This study
- average (standard metabolism x 2)	45,000	4.2	Brodie (1981)
Gray whale - basal metabolism <sup>a</sup>	23,000	4.8	
- average (food removal)	23,000	10.9	Thomson and Martin (1984)
-migrating (7 km/h)	23,000	13.0 <sup>b</sup>	Sumich ( 1983)
Blue whale - basal metabolism <sup>a</sup>	72,000	3.5	
- maintenance (respiration)	70,790	8.4	Lockyer (1981)
- yearly average <sup>a</sup>	72,000	10*2	
Fin whale - basal metabolism <sup>a</sup>	43,500	4.0	
- maintenance (respiration)	43,410	8.9	Lockyer (1981)
- yearly average <sup>c</sup>	43,500	10.8	
Sperm whale - basal metabolism <sup>a</sup>	43,600	4.0	
- average (various)	43,600	20.0	Lockyer (1981)

a From Kleiber's formula.

b Modified to account for smaller lung size as per Thomson and Martin (1984).

c Not including growth.

The apparently low energetic requirement of bowheads relative to some other whales (Table 62) is consistent with the seemingly smaller size of the lungs and heart of the bowhead, along with differences in life history and anatomy. Many whales that have higher metabolic rates-spend their summers in cold high latitude waters, although not necessarily as cold as those occupied by bowheads in summer. However, those other species winter at decidedly lower latitudes than do bowheads. The other species may be imperfectly insulated for either extreme. Their thinner blubber may be necessary to avoid overheating in winter, but may lead to higher rates of heat loss in summer than are experienced by bowheads. Considerable energy may be needed for the long migrations of these other species, and to counteract heat loss in the cold waters where they summer. Thus, these other species may have higher metabolic rates and higher rates of food intake than do bowheads.

Body morphology, insulation and metabolism of bowhead whales, on the other hand, appear to be optimal for conditions in high latitudes. In fact, the bowhead whale could be thought of as a small whale in a parka. The thick blubber is a suitable adaptation in all seasons, since the bowhead never leaves cold waters. Aside from the obvious value of its blubber as insulation, the bowhead's adaptations to cold water may also have been necessitated by the rather impoverished zooplankton populations of the

Beaufort Sea. By operating at metabolic levels near the **basal** metabolic rate, **it** is able to sustain itself on the rather meager plankton resources that are **available** (see '**Zooplankton and Hydroacoustics**' section). Bowheads also appear to have slower growth rates than these other whales. Female **bowheads** reach maturity when they are about 13 m in length (40 MT). They may require 15 or more years **to** reach this size (see Fig. 160 in '**Isotopes**' section, p. 399). Fin whales reach puberty at about the same weight but at an age of **only** about 6 years (Lockyer 1981). This slower rate of growth may reflect lower food availability to bowheads as compared to the other whales. These types of adaptations have been found in some other mammals (**McNab** 1980).

### Energy Requirements of Reproduction and Growth

Reproduction involves a large energy expenditure for females. Energetic requirements for growth are especially great in young animals. These energy requirements are additional to the basic requirements for maintenance, discussed above.

Life History.--Energetic computations for individual bowhead whales and for the population require some data on bowhead life history. Some of these data are **provided** by Davis et al. (1983, **1986a,b**) and **Nerini** et al. (1984). Evidence for some aspects of life history is weak and circumstantial.

Bowhead whales are 4 to 4.6 m long at birth. Mean date of parturition may be in May (Davis et al. 1983). We have no direct data on weight at birth. Extrapolation of our length-weight equation (Table 57) to a 4 m individual yields a weight of 1.7 MT. For comparison, fin **whales** are about 1.8 MT at birth, the smaller sei whales are about 0.75 MT, and **blue** whales are about 2.6 MT (Lockyer 1981). We shall assume a weight of 1.7 MT for newborn **bowhead** whales. In late summer, calves of the year are a mean of 6.45 m (range 4.1 to 7.6 m) in length. **Nerini** et al. (1984) suggest that young bowheads are suckled for about one year. Behavioral observations in August and September show that some calves (most not **measured**) may be separated from their mothers for as much as 1.2 h and then return to suckle (**Würsig** et al. 1985a; this Study). It is not known whether any **calves** are partially weaned at this time. **Thus**, duration of lactation is as yet **unknown**. We shall assume that young are suckled for **one year**.

On the basis of length-frequency data for a small sample of harvested animals, **Nerini** et al. (1984) believed that yearlings are 6.6 to 9.4 m long in spring (mode 8.2 m) and about 10.2 m in autumn. A small peak in their spring length-frequency data at 10.6 m may represent two-year-old animals. **Nerini** et al. (1987) have revised their estimate of the size range of yearlings to 7 to 8.5 m; there is a peak in **their** photogrammetric length frequencies at 8.2 m. Extrapolating from right whale growth data, they estimate that **yearlings** are 8.1 m long, 2 year olds are 10.7 m, and 3 year olds are 11.7 m.

New data on the growth rates of bowheads are inconsistent with some of these previous estimates. Evidence derived from oscillations in the **stable** isotope composition of the baleen suggests a much slower rate of **growth**, at **least** after age 1-2 yr (see '**Isotopes**' section of this report, Fig. 160; also **Schell** et al. in press). **Photogrammetric** data on lengths of individual

bowheads photographed in different years (Davis et al. 1986b; Nerini et al. 1987) also suggest low growth rates for adults and possibly for subadults.

The low and non-linear growth rate suggested by the isotopic evidence (Fig. 160) is unlike that of other baleen whales (cf. Lockyer 1981; Sumich 1986; Aguilar and Lockyer 1987). Thus, the actual growth rate of bowheads remains uncertain. For most adult bowheads, the growth component of the total energy budget is not a large fraction of the total (see below), so uncertainty about growth rates has little effect on the calculations. However, for immature animals and lactating females, uncertainty about growth rate does affect the energy budget. Hence, we have performed separate energetic calculations assuming (a) fast growth by subadults, as suggested by Nerini et al. (1984, 1987), and (b) slow growth, as suggested by the isotopic evidence.

Based on sizes of females with calves, female bowheads become sexually mature at a length of about 13 m. Tarpley (1987a) examined the reproductive tracts of 28 harvested female whales. Immatures had body lengths of 7.6-14.4 m ( $n = 18$ ). Mature females were 14.7-17.7 m long ( $n = 10$ ). Possibly because of small sample size, and stretching of landed whales (Nerini et al. 1987), 14.7 m apparently overestimates the length at maturity in many females. We shall assume that bowheads >13 m are sexually mature and that those <13 m are immature, although we recognize that there is some variation in length at maturity. We also assume a gestation period of one year and a sex ratio of unity (Davis et al. 1983; Nerini et al. 1984).

Lactation. --Several assumptions, based on meager information, must be made in order to calculate energetic requirements of lactation and growth during the early years.

Mean date of birth for bowheads may be in early May at a length of about 4 m. At the end of August, 123 d later, mean length is 6.45 m (Davis et al. 1983). This represents an average length increment of 2.0 cm/d during the first summer after birth. Based on length frequency data, yearlings could be 8.2 m in length in May (Nerini et al. 1984, 1987). The few 'baleen age' data for very young whales are consistent with this 8.2 m estimate (Fig. 160). Thus, weight at one year would be about 11.6 MT, based on the equation in Table 57. If the animal weighs 1700 kg at birth and 6100 kg at length 6.45 m after 123 d, then initial weight gain would be 36 kg/d. If the animal weighs 11.6 MT after one year, then weight gain during the last 242 d of the first year would be 23 kg/d.

Assuming a weight gain of about 36 kg/d over the first 123 d and 23 kg/d over the last 242 d of the year, and active energetic requirements 45% over the basal rate (see 'Comparison of Estimates', above), then the total energy requirement over the first year (computed for each day at the current weight and summed over the year) would be  $244 \times 10^5$  Kcal for maintenance alone, without growth. Weight gain over the year would be 9900 kg. Sei and fin whale muscle has a caloric value of about 1500 to 2600 (mean 1900) Kcal/kg wet weight (Lockyer et al. 1985). Blubber is about 80% oil and wax with a caloric content of 3700 to 7000 (mean 5300) Kcal/kg wet weight (Lockyer et al. 1985). Based on our photogrammetric measurements and assumptions about blubber thickness, blubber is about 48% of total weight in calves (Table 58). Approximately 4750 kg of the first year's weight gain would be blubber. Thus,

total energy required for growth during the first year **would** be about  $350 \times 10^5$  **Kcal**. When this is added to the aforementioned  $244 \times 10^5$  **Kcal** maintenance requirement, the **total** energy requirement in the first year is about  $594 \times 10^5$  **Kcal**.

Assimilation efficiency for milk is about **90%** and cetacean milk contains about **4300 Kcal/kg** wet weight (**Lockyer 1981; Gaskin 1982**). Thus, the female must provide  $660 \times 10^5$  **Kcal** or about 15,300 kg of milk during the year.

Pregnancy.--If we assume **that, at birth**, a **bowhead** calf is 4 m in length and weighs **1700 kg**, then extrapolation of the equations shown on Table 57 yields a value for total blubber content of 49%. Total energy content of the near-term **foetus** would be about  $63 \times 10^5$  **Kcal**. **Basal** metabolism for the **foetus** would be included in energetic requirements for the female **as** determined **by** the respiration method. The additional **energetic** requirements of pregnancy would include only the **calorific** value of the **foetus** or about  $63 \times 10^5$  **Kcal**.

Growth.--For purposes of energetic calculations, we **will** calculate alter energetic requirements assuming both a fast and a slow growth rate.

**Nerini et al.** (1984, 1987) suggest that bowheads may be about 10.7 m and 11.7 m long when two and three years old. Bowheads "of these sizes weigh about 24 MT and 30 MT. If we assume that bowhead growth is similar to that of right whales, maturity may occur after about 7 years. Average weight gain for a subadult would be 5.2 MT/yr. Using our photogrammetric measurements and an assumed blubber thickness of 25 cm; 42% of the gain would be blubber. Total energy required for growth would be an average of  $172 \times 10^5$  **Kcal/yr** for subadults.

If bowheads grow as slowly as suggested by Figure 160 (this report), then growth of subadult bowheads between weaning and puberty could be as little as 1600 kg/yr. Using our photogrammetric measurements as above, total energy required for this growth **would** be about  $53 \times 10^5$  **Kcal/yr**. At puberty fin whales weigh between 44,000 and 48,000 kg and their annual growth increment is 3000 to 3500 kg (**Lockyer 1981**). Assuming that bowheads mature at a length of about 13 m, their weight at maturity would be about 39,600 kg. At first maturity, fin whales are about the same weight as bowhead whales. Young adult fin whales from the southern hemisphere gain about 700 kg/yr and adults about 500 kg/yr (**Lockyer 1981**). We will assume growth of 500 kg/yr for mature bowheads. Mature bowheads are about 40% blubber and a 500 kg/yr gain would represent about  $16 \times 10^5$  **Kcal/yr**.

#### Annual Energy and Food Requirements of Individuals

Computation of total annual energetic requirements must consider timing of migration, length of the stay on the summer feeding grounds, and energetic requirements during each part of the annual cycle. Energetic costs of reproduction and growth must also be included. Annual food intake required to meet all energetic costs is a function of energy requirements and the caloric content of the food. If the required annual intake can be estimated, then the

necessary rate of food intake can be estimated by dividing the **total** annual food requirements by **the** amount of time spent feeding.

Timing and Movements.--Fraker (1979), **Braham et al.** (1980a, 1984), Richardson et al. (1985a, 1987), **Ljungblad et al.** (1986b,c) and **Miller et al.** (1986) have summarized **the** seasonal distribution and migrations of Western **Arctic** bowhead whales. **Bowheads** probably return to wintering grounds in the Bering Sea in November. They pass through the **NE Chukchi** Sea from mid **April** to **early** June and arrive at summering grounds in the eastern **Beaufort** Sea in May and **June**. Peak abundance in nearshore **waters of** the southeastern Beaufort Sea **occurs** in late August. Most **bowheads** migrate west 'through the Alaskan **Beaufort** Sea from mid September to mid October; **they** have **left the** Beaufort Sea by **late** October. In September and **early** October some are-found **off the** coast of Siberia. The total length of the migration is about 2500 km in each direction; the amount of time spent migrating by individual whales is unknown, but may **total 140 d/yr.** This figure includes some days when feeding occurs along the migration route.

Caloric Content of the Bowhead Diet in Late Summer,--The stomach contents of **bowhead** whales taken at Kaktovik showed that **copepods** and **euphausiids** were the dominant food organisms (Table 63; Lowry and Frost 1984). Our data provide information on the caloric content of these organisms in **late** summer. Assuming that Lowry and Frost's data are representative of the average **bowhead** diet in our **study** area, and that our caloric data are **also** representative, the mean caloric **content** of the bowhead diet in the study area in **late** summer is **about 1096 cal/g wet weight (Table 63).**

Mean caloric content of plankton samples taken within concentrated **layers** of plankton in **whale** feeding areas in 1986 was  $1079 \pm \text{s.d. } 128 \text{ cal/g}$ . This value was higher than **that** of plankton taken under any other circumstance (see Table 21 on p. 238).

**Table 63.** Average composition of stomach contents of eight bowheads taken at **Kaktovik** in autumn. Caloric and water content were calculated using 1986 data (Tables 18 and 19).

	% of Contents by Volume <sup>a</sup>	% Water ConCent	cal/g Dry Wt.	cal/g Wet Wt.
Copepods	66.1	81.7	6297	1152
<b>Euphausiids</b>	31.2	80.2	5093	1008
Mysids	<b>1.2</b>	<b>79.9</b>	<b>5126</b>	1030
<b>Amphipods</b>	0.5	<b>83.4</b>	6299	1046
Other invertebrates	0.5	86.0	4500	630
<b>Fish</b>	<b>0.3</b>	<b>83.2</b>	<b>5193</b>	872
<hr/>				
Weighted Mean		<b>81.2</b>	"5865	1096

<sup>a</sup> From Lowry and Frost (1984).

These **data** for caloric content per unit wet weight are less than half the **values** used in previous analyses by Lowry and Frost (1984) and ourselves (LGL and Arctic Sciences 1985). The values used previously were based on Percy and Fife (1980), whose data were apparently biased by underestimating water content and thus wet weight (see Griffiths et al. 1986, p. 125). Our values for water content are consistent with those found by most other authors (Parsons et al. 1977; Ikeda and Motoda 1978).

Estimated Requirements of Individuals. --Table 64 shows the estimated **annual** energetic requirements for calves, **subadults**, and adult males; for non-reproductive, pregnant and lactating females; and for average adult females. Some of the main assumptions and procedures were as follows:

1. The annual maintenance rate was calculated using the respiration method. Respiration includes the metabolic costs of growing, producing **milk**, and metabolism of the **foetus**. It does not include the **calorific** value of the weight gained, the milk that was produced, or the foetus itself. These **are** shown as separate **items**. The **annual** maintenance rate for a calf was estimated by calculating the basal metabolic rate for each day, given the weight increases discussed above and adding 45% for active metabolism.
2. Energetic costs of pregnancy and lactation averaged over an assumed **3-yr** reproductive cycle are shown for a mature female.
3. Migration to and from summer feeding grounds **was** assumed, in the absence of **direct data**, to take 140 d. This includes some time spent traveling within the summer and winter grounds. Energetic requirements during migration were computed using average respiration rates of migrating animals. It should be noted that some feeding occurs during part of both migrations (Lowry and Frost 1984; Ljungblad et al. 1986a; Carroll et al. 1987; Lowry et al. 1987; this study). Blow rate for traveling **whales** was 0.66 to 0.73 blows/rein in the western **arctic** (Table 59). For whales engaged in **all** activities in the western arctic during **fall**, the mean blow rate was 0.66 blows/rein according to Ljungblad et al. (1984b) and 0.70 blows/rein in the present study (Table 59). The weighted average from these **two** studies was 0.68 blows/rein for all activities recorded during fall migration. This 0.68 figure is used here as an estimate of breathing rate during migration.
4. Mean blow rate of all non-calves observed in the Canadian Beaufort Sea (Würsig et al. 1985b) was used to estimate energetic requirements in summer (0.77 blows/rein, Table 59).
5. In the absence of any behavioral observations in winter, the mean **blow** rate for non-calves observed during migration (0.68 blows/rein) was assumed to **apply** in winter as **well**. Migration appears to be a less strenuous activity than summer feeding. Hence, data from the migration period **are** used to approximate **blow rates** in winter, when the whales are presumably less active than in summer.

6. Assimilation efficiencies for fin whales *were* used to estimate the energy intake required to meet energetic requirements of bowheads. These assimilation efficiencies are similar to those of carnivores (75%; Lockyer 1981) but much higher than for herbivores (53% for a cow; Kleiber 1961). Lockyer (1981) derived an assimilation efficiency of 87% for pregnant or lactating female **rorquals**. This **value** is higher than for **males, subadults** and nonreproductive females (77-79%; cf. Lockyer 1981). This is clearly an oversimplification; it leads to a lower predicted energy requirement for a pregnant than for a nonreproductive female--an unrealistic result. We have therefore assumed that assimilation efficiency for pregnant and lactating females is only slightly higher (80%) than that of other groups in the population.
7. The total **metabolizable** energy cost of gestation is equivalent to about twice the basal metabolic rate of the foetus as predicted from Kleiber's equation (Lavigne *et al.* 1982). Assuming a 365 day gestation period and a birth weight of 1700 kg for a **bowhead**, total **metabolizable** cost of pregnancy would be about  $69 \times 10^5$  Kcal, or about 5% of the total annual maintenance expenditure of an adult female. An estimate of energetic requirements derived from the respiration method includes **all metabolizable costs**, including costs associated with gestation. Not included is the **calorific** value of the foetus itself ( $63 \times 10^5$  Kcal) and this is shown as a separate item in Table 64e
8. The biomass of food required to meet these requirements was estimated based on an estimate of average caloric content of **zooplankton** in the area where whales were feeding. In September, we measured the caloric content of **zooplankton** within the concentrated plankton layers that we detected by echosounder and net sampling over the inner continental shelf. Caloric content recorded in the Canadian Beaufort Sea in late August-early September 1986 was similar to that in the Alaskan Beaufort in September (Tables 18 and 27). We used our September figure of 1079 cal/g wet weight (Table 21), based on sampling within **zooplankton** layers in whale feeding areas, for both August and September. Caloric content of **zooplankton** is lower earlier in the summer. For example, caloric content of copepods in Frobisher Bay was 11% lower in July than in September (Percy and Fife 1980). In the Bering Sea, caloric content of euphausiids was 6 to 19% lower in spring than in fall (Harris 1985). For the months of June and July, we assume that caloric content is 10% lower than our September estimate of 1079 cal/g wet weight. Thus, an overall average caloric content of 1025 cal/g wet weight is assumed for food consumed in the June to September period.

The greatest uncertainty is the unknown amount of feeding that occurs in winter and along the migration route. Three estimates of feeding rates have been computed in Table 64, assuming that feeding occurs over (a) 105 d, (b) 130 d, and (c) 165 d. The 130 d figure is the one used by Lowry and Frost (1984). Based on seasonal changes in the isotopic composition of the baleen, muscle and visceral fat, Schell *et al.* (this report, 'Isotopes' section) believe that bowheads do feed in winter. However, the amount of feeding in

Table 64. Estimated annual energetic requirements, food requirements and feeding rates of Western' Arctic bowhead whales. A slow rate of growth by subadults is assured.

	Calf	Subadult	Adult Male	Non-Reproductive Female	Pregnant Female	Lactating Female	Average Adult Female <sup>a</sup>
Mean Length (m)	6.4	10.8	14.5	14.5	14.5	14.5	14.5
Mean Weight (kg)	6200	24900	53700	53700	53700	53700	53700
Lung volume (L) <sup>b</sup>		373.5	805.5	805.5	805.5	805.5	805.5
Vital capacity (L) <sup>b</sup>		298.8	644.4	644.4	644.4	644.4	644.4
Oxygen utilization (L) <sup>b</sup>		29.9	64.4	64.4	64.4	64.4	64.4
Migration (blows/min)		0.68	0.68	0.68	0.68	0.68	0.68
(Kcal/d x 10 <sup>5</sup> )		1.39	3.00	3.00	3.00	3.00	3.00
Total (140 d; Kcal x 10 <sup>5</sup> )		195	420	420	420	420	420
Summer (blows/min)		0.77	0.77	0.77	0.77	0.77	0.77
(Kcal/d x 10 <sup>5</sup> )		1.57	3.39	3.39	3.39	3.39	3.39
Total (100 d; kcal x 10 <sup>5</sup> )		157	339	339	339	339	339
winter (blows/min)		0.68	0.68	0.68	0.68	0.68	0.68
(Kcal/d x 10 <sup>5</sup> )		1.39	3.00	3.00	3.00	3.00	3.00
Total (125 d; kcal x 10 <sup>5</sup> )		174	375	375	375	375	375
Total annual maintenance (Kcal/yr x 10 <sup>5</sup> )	244 <sup>c</sup>	526	1134	1134	1134	1124	1134
Growth (Kcal/yr x 10 <sup>5</sup> )	350	53	16	16	16	16	16
Lactation (Kcal/yr x 10 <sup>5</sup> )						660	220
Pregnancy (Kcal/yr x 10 <sup>5</sup> )					63		21
Total annual requirements (Kcal/yr x 10 <sup>5</sup> )	594	579	1150	1150	1213	1810	1391
Assimilation <sup>d</sup> x 10 <sup>5</sup>	0.90	0.79	0.79	0.77	0.80	0.80	0.80
Annual food requirements (Kcal/yr x 10 <sup>5</sup> )	660	732	1455	1493	1516	2262	1738
(kg/Yr)	15,349 <sup>e</sup>	71,458 <sup>f</sup>	141,970	145,658	147,878	220,697	169,584
Average daily rate (kg/d)		196	389	399	405	605	465
<b>State of food intake</b>							
No Winter feeding							
Feeding 105 d (kg/d)		681	1352	1387	140a	2102	1615
Feeding 130 d (kg/d)		550	1092	1120	1138	1698	1304
Feeding 165 d (kg/d)		433	860	883	896	1337	1028
With winter feeding <sup>g</sup>							
Feeding 130 d (kg/d) 10% /d		514	1022	1048	1064	1588	1221
Feeding 130 d (kg/d) 30% /d		444	881	904	918	1370	1053

<sup>a</sup> Cost of reproduction averaged over 3 yr.

<sup>b</sup> Lung volume in L is 1.5% of body weight in kg. Vital capacity = 80 % of total volume. Oxygen utilization = 10% of vital capacity.

<sup>c</sup> Computed as basal metabolic rate x 1.45. Calculated for each day and summed over the year.

<sup>d</sup> Fran Lockyer (1981) for equivalent sized fin whale.

<sup>e</sup> Milk.

<sup>f</sup> Mixed zooplankton available to bowheads in layers of concentrated zooplankton in September 1986: 1079 cal/g wet weight for August and September, 10% less in June and July.

<sup>g</sup> Assuming that feeding in winter and during migration provides 10% or 30% of daily energy requirements.



winter is still uncertain, so we continue to show the calculated **daily** requirements based on a variety of assumptions about the number of days of feeding per year.

If feeding occurs for 130 d in summer and not at **all in** winter, the above assumptions **result in an** estimated **daily zooplankton intake** of about 550 kg/d for an average **subadult whale**, about 1090 kg/d for an **adult male**, and about 1300 kg/d for an average **adult female**. A lactating female would have the highest food requirement, about 1700 kg/d. This **last** figure is an upper **limit** because it assumes that **she would** maintain her body weight over the year of **lactation--an unlikely** proposition. The rate of food intake **would** be higher if feeding occurs on <130 d/yr, and **lower if** feeding **occurs on** >130 d/yr (Table 64).

Another uncertainty in these calculations is the rate of growth of **subadults**. If growth of **subadults** is as rapid as suggested by Nerini et al. (1987), **subadults** would require about  $883 \times 10^5$  Kcal/yr; this is about 21% higher than the  $732 \times 10^5$  Kcal/yr calculated on the assumption that growth is slow (Table 64). If the faster rate of growth is correct, **subadults** would have to consume 663 kg/d assuming 130 d feeding in summer and no winter feeding, or 535 kg/d if feeding in winter provided 30% of daily maintenance requirements.

A further concern regarding energy requirements of **subadults** is the possibility that the length-weight relationship derived by our photogrammetric analysis (Table 57) may overestimate **weights**, at least of **subadults**. If so, **their** energetic requirements for growth would also be overestimated. J.C. George (North Slope Borough, Barrow, AK, pers. comm.) recently weighed an 11 m bowhead as it was being butchered. Total weight including a 6% allowance for blood loss was 14.8 MT. Blubber was 44% of total weight. The length-weight relationship derived from our photogrammetric analysis predicts a weight of 25 MT for an 11 m bowhead, and predicts that a 14.8 MT animal would be about 9 m long. An 11 m bowhead that was 14.8 MT would be heavier than an 11 m fin whale but lighter than an 11 m right whale.

<u>Species</u>	<u>Weight at 11 m</u>	<u>Reference</u>
Bowhead whale	14.8 MT	C. George (pers. comm.)
Bowhead whale	. 25	This study
Fin whale - Northern Hemisphere	6.0	Lockyer and Waters (1986)
- Antarctic	10.3	Lockyer (19'76)
Right whale	19.1	Lockyer (1976)

In bowheads, a **small** increment in length is accompanied by a **large** increment in weight (Fig. 165). Thus, the fast **rate** of growth in length implies **large** weight increases and large energetic requirements. However, if the length-weight relationship of the **whale** measured by C. George is representative of **subadult** bowheads, then a fast rate of growth in length would be accompanied by more **modest** increases in weight and lower energetic requirements than are assumed in our calculations. **Clearly**, more measurements of the actual weights of known-length bowheads would be extremely helpful in resolving various issues about length-weight relationships growth rates, and energetic requirements.

Our estimates of food consumption are considerably higher than those of both Lowry and Frost (1984) and LGL and Arctic Sciences (1985). Both of those **analyses** used Percy and Fife's (1980) data from Frobisher Bay to estimate caloric content of **bowhead** food. However, the dry weight to wet weight ratio found by Percy and Fife (1980) for crustaceans is not applicable to this study (see **Griffiths** et al 1986, p. 125 and Table 63). Use of the Frobisher Bay results led to an overestimation of **cal/g** wet weight, by a factor of about 2, in the earlier analyses. Other reasons for the higher estimates found in this study than by Lowry and Frost (1984) are described by Thomson (1986, p. 241).

#### Annual Population Requirements

To estimate the energy requirements of the bowhead population, we need to know the number of whales in each of the categories for which we have estimated the individual annual energy needs. The most recently published 'best estimate' of the number of bowheads in the Western Arctic population is 4417 with 95% confidence limits 2613-6221 (**I.W.C.** 1986). For illustrative purposes we have assumed, based on data in Davis et al. (1983, p. 79), that 10.6% of the population would be calves, 52.3% subadults, **18.6% adult males**, and 18.6% adult females. Our analysis excludes the calves, whose energy is acquired from lactating females. Davis et al. (1983) noted that their data on whale sizes were probably biased in favor of **subadult** age classes (defined as whales <13 m long). If so, the energetic requirements of the entire population as shown in Table 65 would probably be underestimates. However, **photogrammetric** data from the summers of 1983-86 (**Cubbage et al. 1984; Würsig et al. 1985b; Davis et al. 1986a,b; Cubbage and Calambokidis 1987a,b**) showed even higher percentages of subadults than were found in 1982 by Davis et al. (1983). Also, data from the spring migration period in 1985 (**Nerini et al. 1987**) provided a similar adult : subadult ratio as was found in the summer of 1982. Thus, we have used the 1982 results as being most representative of abundances of different size classes.

A population of 4417 bowheads would consume approximately  $4.2 \times 10^5$  metric tons of **zooplankton** per year (Table 65). This estimate exceeds our earlier estimate (LGL and Arctic Sciences 1985), mainly because of the lower caloric content per unit wet weight measured in this study. In the 'Integration' section of this report, later, we compare this population requirement with the available amount of concentrated zooplankton in the Beaufort Sea. The number of bowheads in the Western Arctic population could be as high as 7200 animals (**I.W.C.** in prep.). If so, the population would consume  $6.9 \times 10^5$  metric tons of **zooplankton** per year (Table 65).

#### Feeding Rates

Feeding rates can be estimated from data on swimming speeds, distance travelled per dive, hours of feeding per day, cross-sectional area of mouth, and zooplankton biomass. We have estimated swimming speeds and approximate distances travelled per dive for **bowheads** that were believed to be feeding (see p. 353). Cross-sectional area of the mouth opening was also computed earlier (Table 58). We assume a 130 d summer feeding season (Lowry and Frost 1984), a swimming speed of 5 km/h, and 100% filtration efficiency. For illustrative purposes, time spent feeding is assumed to be either 12 or 16

Table 65. Estimated energetic requirements of the Western Arctic population of **bowhead** whales.

	<b>Subadults</b>	<b>Adult Males</b>	<b>Adult Females</b>	<b>Total</b>
<b>% of population</b>	<b>52.3</b>	<b>18.6</b>	<b>18.6</b>	<b>89.5<sup>d</sup></b>
Individual <b>annual</b> food requirements <sup>b</sup>				
<b>Kcal x 10<sup>8</sup>/animal/yr</b>	0073	<b>1.46</b>	<b>1.74</b>	
<b>Kg x 10<sup>5</sup>/animal/yr</b>	0.71	<b>1.42</b>	<b>1.70</b>	
<b>Kg/d<sup>c</sup></b>	550	1092	<b>1304</b>	
Number of animals = 4417 <sup>e</sup>	<b>2310</b>	822	822	<b>3954<sup>d</sup></b>
Population requirements <sup>e</sup>				
<b>Kcal x 10<sup>8</sup>/yr</b>	<b>1692</b> "	1196	<b>1428</b>	<b>4316<sup>d</sup></b>
<b>Kg x 10<sup>5</sup>/yr</b>	<b>1651</b>	<b>1166</b>	<b>1393</b>	4210
<b>Kg x 10<sup>5</sup>/d<sup>c</sup></b>	<b>12.7</b>	<b>9.0</b>	<b>10.7</b>	32.4
Number of animals = 7200 <sup>f</sup>	3765"	1340	1340	<b>6445<sup>d</sup></b>
Population requirements <sup>f</sup>				
<b>Kcal x 10<sup>8</sup>/yr</b>	.2758	<b>1949</b>	2 3 2 8	<b>7035<sup>d</sup></b>
<b>Kg x 10<sup>5</sup>/yr</b>	<b>2691</b>	<b>1901</b>	2271	6863 "
<b>Kg x 10<sup>5</sup>/d<sup>c</sup></b>	<b>20.7</b> "	<b>14.6</b>	<b>17.5</b>	<b>52.8</b>

a From Davis et al. (1983, p. 79) and an assumed sex ratio of 1:1.

b From Table 64.

<sup>c</sup> Assuming feeding for 130 d.

d Does not include calves, whose energy comes from lactating females.

e Assuming population of 4417 bowheads (I.W.C. 1986).

<sup>f</sup> Assuming population of 7200 bowheads (I.W.C. in press).

hours/day during summer. Separate calculations are done assuming **that** feeding during winter **and** migration is (a) negligible, or (b) equivalent to 30% of average **daily** maintenance requirements. The annual food requirements calculated in Table 64 are assumed; these values assume a **slow** growth rate for **subadults**. From the various assumptions, **it** is possible to calculate **the** average biomass of **zooplankton** that would have to be **found** in bowhead feeding locations in **order** to meet theoretical energy requirements. **Biomasses** calculated in this way range from 2.1 to 4.1 g/m<sup>3</sup> on a wet weight basis (Table 66).

Table 66. Average zooplankton biomasses required in summer feeding locations based on various assumptions about winter feeding and hours of feeding per day in a 130 d summer season. These calculations are based on energetic requirements calculated using the slow growth rate (Table 64).

Zooplankton Biomass Required ( $\text{g}/\text{m}^3$ ) <sup>a</sup>				
	Sub- adult	Adult Male	Adult Female	Average Whale
Assuming No Winter Feeding				
Feeding 12 h/d	3.4	3.4	4.1	3.4
" 16 h/d	2.5	2.06	3.01	2.5
Assuming Some Winter Feeding <sup>b</sup>				
Feeding 12 h/d	2.7	2.8	3.3	2.7
" 16 h/d	2.1	2.1	2.5	2.0

<sup>a</sup> Average cross-sectional area of the mouth is assumed to be  $2.7 \text{ m}^2$  for subadults,  $3.3 \text{ m}^2$  for adults, and  $3.9 \text{ m}^2$  overall, (Table 58).

<sup>b</sup> Feeding during winter and migration = 30% of daily maintenance requirements.

If bowheads feed in winter and during migration, then they would require a lower daily intake and lower prey densities in summer. If an average subadult met its daily energetic requirements every day throughout the year, then it would need to consume  $196 \text{ kg}/\text{d}$  and would have to feed for 16 h/d in zooplankton concentrations of  $0.9 \text{ g}/\text{m}^3$  or for 12 h/d in  $1.2 \text{ g}/\text{m}^3$ . It appears unlikely that bowheads meet all of their daily requirements during winter and migration, but there is evidence that they do some feeding during these periods. Thus,  $0.9 \text{ g}/\text{m}^3$  could be considered as the lower end of the range of subadult food requirements. Assuming the faster rate of growth, no winter feeding and feeding for 12 h/d, a subadult would have to feed in concentrations of  $3.4 \text{ g}/\text{m}^3$ . This figure could be considered as the upper end of the range of subadult food requirements.

Zooplankton have been collected near feeding bowheads during this study and in the Canadian Beaufort Sea by Bradstreet and Fissel (1986) and Bradstreet et al. (1987). Sampling depths and locations were selected with the aid of echosounders that detected the presence of layers of concentrated zooplankton. The maximum zooplankton biomasses found at any one depth averaged  $2.0 \pm \text{s.d. } 0.7 \text{ g}/\text{m}^3$  ( $n=8$ ) during sampling at feeding stations in the Canadian and Alaskan Beaufort Sea (see 'Zooplankton and Hydroacoustics', p. 249; excludes Yukon stn 1986-3, where definite evidence of feeding was not observed). Bowheads selectively feed in areas with a higher than average

biomass of **zooplankton**, and measured **biomasses** in feeding areas are similar to calculated theoretical requirements (cf. Table 66). Observed **biomasses** at feeding locations average slightly lower than calculated requirements, but the observed biomasses are probably underestimated somewhat because of **the** inevitable sampling problems in studies of **zooplankton** patches.

The isotopic evidence suggests that there is **considerable** feeding outside **the** eastern Beaufort Sea, **at least in subadults** (see 'Isotopes' section). **Some** bowheads are known to feed during migration. For the purposes of the discussion that follows ('Integration' section), we will assume that the average daily intake of bowheads while migrating and **while on** the winter grounds is 30% of average **daily** maintenance requirements (**i.e.** 30% of 196 kg/d for **subadults**, Table 64). **If so, subadults would have to** consume 444 kg/d in **summer**, which **would** require feeding for 16 h/d in **zooplankton** concentrations of 2.1 g/m<sup>3</sup> or for 12 h/d in 2.7 g/m<sup>3</sup> (Table 66). **If all bowheads consumed 30% of daily maintenance requirements during winter, the entire population would consume about 20% of its energetic requirements during migration and while on the wintering grounds.**

Bowheads are unusual among the baleen whales in that their stomachs are relatively small. Bowheads 9 to 9.5 m long (about 16 MT) have a total stomach volume of about 100 L (Tarpley 1987b). Based on the assumptions in Table 64, **and** assuming that feeding in winter **and** during migration provides 30% of **daily** requirements, a whale this size must consume about 300 kg of **zooplankton** per **day**. The stomach would hold only **about** 1/3 of **the** daily **ration** at one time. The **usual** amount of food in whales taken in the feeding season is about 300 kg in Antarctic sei whales weighing 15 MT, about 800 kg in fin whales, and about 500 kg in humpbacks (Zenkovich 1969 in Lockyer 1981). In the case of fin **whales**, the stomach can hold at least **half** of the daily energetic requirements. These whales often consume a **large meal early** in the day and then feed sporadically throughout the day (see Lockyer 1981). They feed in **the** Antarctic where prey densities can reach 2000 g/m<sup>3</sup> (Lockyer 1981)--much higher than ever found in the **Beaufort** Sea. A 9.25 m bowhead with a mouth area of 1.83 m<sup>2</sup> could consume about 18 kg/h while feeding **ata** speed of 5 km/h in **zooplankton concentrations** of 2.0 g/m<sup>3</sup>. Observed **prey** densities are unlikely to afford opportunities for rates of feeding that **are much** higher. Thus, a bowhead probably has little need of a **larger** stomach. The small stomach also implies that feeding must occur over a protracted portion of the day.

There are still many uncertainties in our estimates of the energetic requirements of bowhead whales:

1. Improvements in the estimates **will** require better information about various aspects of bowhead physiology growth, population composition, and behavior. **The stable** isotope approach may provide a method for **the** estimation of bowhead growth rates. However baleen **wear** limits the record contained in the baleen to about 20 years. Further work using this technique may provide specific data on growth rates. Despite the uncertainties, the theoretical estimates are generally consistent with direct observations of feeding durations and **zooplankton** biomass at feeding locations. Similarly, feeding rates of blue, fin and gray whales in nature are generally consistent

with the theoretical estimates for these species (**Lockyer** 1981; Thomson and Martin 1984). Two major improvements in this report, relative *to* previous estimates, are the use of our direct measurements of (a) the caloric content, per unit wet weight, of the food available within the study area, and (b) the quantities of food available at locations where bowheads feed.

2. It is known that some bowheads feed at least sparingly during spring and autumn migration west of the study area. Some feeding may occur in the Bering Sea during winter, but **zooplankton** biomass and caloric content in winter are probably lower than in summer. There are no direct observations of either food availability or bowhead behavior in winter (see '**Integration**', P<sup>4</sup> 471-2). The analyses of carbon isotope composition of **bowhead** tissue in spring and **fall**, although based **on small** sample sizes, suggest that **subadults** obtain considerable food in areas outside the eastern Beaufort Sea. However it is not **yet** possible to determine the proportion of annual requirements that are acquired in winter.
3. A reliable estimate of the cross-sectional area of the mouth opening **while** feeding is critical to an estimate of feeding rates in nature. The estimate used here is 4.6 m<sup>2</sup> for an average adult. With our value, the prey density necessary to *sustain* bowheads is 4.6 times lower than that required by **Brodie's** assumed value of 1 m<sup>2</sup>.
4. Most of the information dealing with prey availability comes from areas frequented **by subadult** whales. **The -feeding grounds** of mature animals, and especially of lactating females, are not **well** documented. Adults have higher energetic "requirements than **subadults** and apparently require slightly higher prey densities to meet these requirements (Table 66).

There **is** general agreement between observed prey densities and the energetic requirements of gray whales (Thomson and Martin 1984), Antarctic **rorquals** (**Lockyer** 1981), northern right whales (Mayo et al. 1985), and bowhead whales (this report). Recent findings that theoretical estimates of food requirements are similar to food availability are related to **two** developments:

1. Energetic requirements of marine mammals are lower than had been believed previously, and are similar to those of terrestrial mammals of corresponding size (**Lavigne** et al. 1986).
2. Techniques for estimating food availability, especially in the case of **zooplankton**, are becoming more sophisticated. This has resulted in increased "estimates of potential food availability in patches of concentrated prey.

Since reproductive success, growth rates and age of maturity may be closely linked to food availability (**Lockyer** 1978, 1986; **McNab** 1980), energetic and feeding studies such as these may provide valuable background data for the **study of** cetacean population dynamics.

### Conclusions

1. Energy requirements of bowhead whales are somewhat uncertain because of uncertainties about bowhead sizes, length-weight relationships, physiology, growth rate, and population composition. However, the **apparent** energy needs of bowheads are generally consistent with what **is** known about other large whales. Also, most of the different methods for calculating energy needs give similar results. **Food** requirements and food availability **can** be estimated with sufficient accuracy to warrant comparison.
2. **The** energetic requirements of bowhead whales as estimated using the respiration method are similar to estimates based on calculated power **output** or hydrodynamic considerations, but higher than estimates based on **Brodie's (1981)** standard metabolism approach. The theoretical energy requirements of bowheads appear to be somewhat lower than those of other large whales.
3. One uncertainty affecting the **energetic** analysis has been the unknown amount of feeding in winter and during migration around western Alaska. Isotopic results obtained in 1986 suggest that there is a significant amount of feeding outside the Beaufort **Sea**, at least by **subadults**. Thus, most of our calculations assume a high feeding rate for **130 d** in summer and **early** autumn, and a lower feeding rate (30% of daily maintenance **rate**) for the *rest* of the year. Other feeding scenarios *are* also considered (Tables 64-66).
4. **The** annual food requirement for a population of 4417 bowheads is estimated to be about 421,000 MT, with broad confidence limits. This value is higher **than** some previous **estimates**, primarily because **the** caloric content of **zooplankton** in the Beaufort Sea, on a wet weight basis, is substantially lower than was assumed in some previous analyses of **bowhead** energetic. Numerous other refinements in the estimation process are described in this report. If the population size **is** about 7200 whales rather than about **4417**, the total annual food requirement **would** be proportionally greater--about 690,000 MT.
5. Based on our energetic model, an average bowhead **would** have to feed at locations where average **zooplankton** biomass is at least **2.5 g/m<sup>3</sup>** if it must meet its annual food **requirements** in 130 d, feeding for 16 h/d. The average prey biomass at summer feeding locations would need to be 2.0 g/m<sup>3</sup> if 30% of daily maintenance requirements were met by supplementary feeding during the remainder of **the** year.
6. Required prey **biomasses**, on a 'per cubic **meter**' basis, appear to be similar for **subadults** and **adult males** but higher for **adult** females. This assumes that **subadults** grow at the **slow** rate implied by analyses of baleen. Required prey **biomasses** for subadults would be significantly higher (by about **21%**) if they grew at the faster rate previously assumed. The apparent slow growth **rate** may be *an* adaptation to the relatively low **zooplankton** biomasses available in the Beaufort Sea.

7. **Zooplankton** abundance at feeding sites in the **Beaufort** Sea, including parts of the Eastern Alaskan Beaufort Sea, is consistent with the theoretical estimates of the energy needed by individual bowheads on a daily basis. The contribution of the concentrated prey within the study area to the annual energy requirement of the bowhead population is addressed in **the** following 'Integration' section.



## INTEGRATION\*

. . .

This section discusses the results and conclusions from prior sections, but is primarily intended to integrate this **'disciplinary'** information in order to provide, insofar as the **data allow**, definitive conclusions regarding the overall purpose of the study.

The overall objective of the study was to evaluate the importance of **the Eastern Alaskan Beaufort Sea** as a feeding area **for the Western Arctic (=Bering Sea) population of bowhead whales**. The null hypothesis, as specified **by MMS**, was that **'Food resources consumed in the Eastern Alaskan Beaufort Sea do not contribute significantly to the annual energy requirements of the Western Arctic bowhead stock.'**

To test this hypothesis, it was necessary to determine

1. the seasonal and spatial patterns of utilization of the **study area by bowhead whales**, with emphasis on the identification of feeding areas;
2. the availability **in** those areas of the **zooplankton** on which bowheads feed; and
3. the degree *to* which the prey acquired in the Eastern Alaskan Beaufort Sea **meets** the annual food requirements of individuals and of **the** population.

The **'Bowheads'** and **'Zooplankton and Hydroacoustics'** sections of this report have presented our 1985-86 results concerning topics 1 and 2, and have discussed those results in relation to previously available information. **Background information** regarding topic 3 is given in the **'Isotopes'** and **'Energetics of Bowheads'** sections. **In** this section, we integrate the results and conclusions of the **previous** sections by first testing the overall **null hypothesis** and then describing specific bowhead feeding areas within the study area in terms of their **zooplankton** and physical oceanography. Bowhead feeding **in** the study area is then **put** into perspective **by** evaluating bowhead feeding **over** other parts of the range. **In the last part of** this integration, we discuss ways in which offshore exploration for oil **and** gas might reduce prey availability or bowhead feeding in the study area.

### Energetic Importance of the Study Area to Bowheads

The null hypothesis being addressed by this study is that **'Food resources in the Eastern Alaskan Beaufort Sea do not contribute significantly to the annual energy requirements of the Western Arctic bowhead stock'**. This hypothesis can be tested by comparing the total energy requirements **of** the population with estimates of (1) the **total** amount of **zooplankton** available to bowheads within the study area and (2) the amount of **zooplankton** consumed by bowheads within the study area. If the amounts of **zooplankton** available to and/or consumed by bowheads are **small** relative to total **annual** population requirements, then the **null hypothesis would** be accepted.

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### Zooplankton Available to Bowheads in the Study Area

**Total Zooplankton Available.--Zooplankton** sampling in the Eastern Alaskan Beaufort Sea during September 1985-86 was confined to the continental shelf area where water depths are <200 m. Most of the bowhead feeding within the study area is in waters <200 m deep. In 1985, about 68,000 MT of zooplankton was present in the top 50 m of the water column in parts of the official study area with water' depth <200 m (Table 67). The corresponding figure for 1986 was 80,000 MT. Because of the inherent difficulties in sampling zooplankton, the **small** difference between the two years is **not** significant.

**Table 67. Estimated total wet weight of zooplankton in the upper 50 m of the study area in 1985 and 1986.**

Region	km <sup>2</sup>	mg/m <sup>3</sup> <sup>b</sup>		Depths (m) Considered <sup>b</sup>		Biomass (MT) <sup>c</sup>			
		1985	1986	1985	1986	1985	1986		
<hr/>									
Shelf, 0-200 m Deep									
" Nearshore	844	(2815) <sup>a</sup>	455	285	"	7-15	4-23	3 4 5 7 16	043
Inner shelf	4220	(2249) <sup>a</sup>	266	283		7-35	4-45	32590	26728
Outer shelf	3376		214	232		7-50	4-50	" 31784	36859
	<hr/>							<hr/>	.
subtotal	8440							67831	7%30
slope, 200-2000 m Deep	7589		100	100		7-50	4-50	33392	35668
>2000 m Deep	9441	.	100	100		7-50	4-50	41540	44373
	<hr/>							<hr/>	<hr/>
subtotal	17030							74932	80041
<hr/>									
Total	25470							142763	"15%71

<sup>a</sup> The extent of the nearshore zone, as defined by water mass characteristics, was different in 1985 and 1986. Figures in parentheses are estimates for 1986.

<sup>b</sup> Depth = 50 m or average depth of water, whichever was less. Top few meters of water, where there was little zooplankton, are not considered. Estimated from acoustic data for continental shelf zone and from net tows made in October 1986 for depths >200 m (Tables 16 and 21, p. 226 and 237).

<sup>c</sup> Biomass in top 50 m (excluding top 4 m in 1986 and 7 m in 1985), in metric tons.

Data from October 1986 were used to estimate the amount of **zooplankton** farther offshore in the study area. We assumed that the mean zooplankton biomass of 100  $\text{mg}/\text{m}^3$  found in the top 50 m over the continental slope was also representative of biomass beyond the slope. Thus, total zooplankton biomass in the top 50 m between the 200 m contour and the northern edge of the study area (71°30'N) was about 77,000 MT (Table 67).

The total estimated zooplankton biomass in the upper 50 m of the water column within the study area during September of 1985-86 was about 150,000 MT. Additional zooplankton was present below 50 m depth in waters that were >50 m deep, but the hydroacoustic surveys indicated that dense zooplankton concentrations were uncommon below 50 m during September.

Concentrated Zooplankton Available. --Considerable effort was devoted during this study to documenting the vertical and horizontal variability in zooplankton biomass. This was done because we expected, based on theoretical calculations of energy requirements and evidence from other species of baleen whales, that feeding would be concentrated at locations with above-average prey densities.

Other species of baleen whales feed preferentially in areas with a higher than average biomass of "potential prey. On a broad scale, fin whales near Iceland concentrate in a semipermanent area of upwelling where zooplankton biomass is 4-9 times higher than in surrounding areas (Foerster and Thompson 1985). On a smaller scale, fin whales typically feed at specific sites where prey concentrations are many times denser than those in surrounding waters (Brodie et al. 1978). The distribution and movements of humpback whales off Newfoundland and New England are closely related to the distribution and movements of schooling fish (Whitehead and Carscadden 1985; Whitehead and Glass 1985; Payne et al. 1986). In southeastern Alaska, Bryant et al. (1981) related changes in distribution of humpbacks to changes in abundance of their prey, and Dolphin (1987) showed that feeding locations and depths are sometimes closely related to those where dense euphausiid concentrations occur. In the northern Bering Sea, the distribution of gray whales and the density of feeding traces left on the sea bed by this benthic-feeding species were closely correlated with biomass of potential prey (Thomson and Martin 1984). Baleen whales apparently cannot obtain enough food by feeding in areas of average prey abundance; they must feed selectively in areas of concentrated prey (Nemoto 1970; Brodie et al. 1978; Kenney et al. 1986). Thus, to measure food availability to baleen whales, it is necessary to measure the small-scale variability and patchiness of the prey, not just average prey biomass (Crowley 1977; Hunt and Schneider 1987).

Bowheads, like other baleen whales, feed preferentially in areas with a higher than average biomass of zooplankton (Griffiths and Buchanan 1982; Bradstreet and Fissel 1986; Bradstreet et al. 1987; this study). Thus, much of the zooplankton in the study area at anyone time must occur in concentrations that are too low to permit economical feeding. We expected (and observed) that most feeding would be in areas where the zooplankton density is greater than a threshold biomass representing the minimum concentration for economical feeding (see Table 66 on p. 444; Table 68). Feeding in concentrations of food less dense than the feeding threshold, if continued for significant periods, would not allow a whale to meet its daily food requirements. This would

Table 68. Characteristics of bowhead feeding areas. Mean biomass is biomass in oblique tows. Maximum biomass is the biomass in the horizontal tow with the largest biomass at each station; these horizontal tows were guided to the depth of maximum biomass via echosounder. The depth at which the maximum biomass occurred is also shown. Other relevant biomass estimates in horizontal tows are also shown. Dominant taxa in oblique tows or, when unavailable in horizontal tows, are shown.

Zooplankton								
Location	Date	Water Depth (m)	Biomass (mg/m <sup>3</sup> )		Depth of Max. Biomass (m)	Dominant Zooplankters		Bowheads
			Mean	Maximum		Taxa (X)	Species (%)	
Thie Study								
1. Off Kongakut Delta 69°50'N 141°52'W	5 Sep 86	14	1228	3023'	10	Copepods (96%)	<u>Limnocalanus macrurus</u> (95%)	Feeding whales observed from boat and aircraft
2. 69°49'N 141°51'W	6 Sep 86	11	853, "318	2886	8	Copepods (91X)	<u>Limnocalanus macrurus</u> (88%)	Feeding whales observed from boat and aircraft
3. 69°50'N 141°36'W	7 Sep 86	22	912	"2137	15 "	Copepods ( 9 5 % )	<u>Limnocalanus macrurus</u> (94X)	Feeding whales observed from boat and aircraft
4. West of Herschel Is. 69°36'N 139°32'W	4 Sep 86	17	96	75	8	Hydrozoa + Ctenophores (38X)	<u>Aglantha digitale</u> (26X) ,	None seen from boat; feeding whales seen from aircraft previous day
5. Off Clarence Lagoon 69°38'N 140°49'W	7 Sep 86	12	105	3847	8	Hydrozoa + Ctenophores (42X)	<u>Limnocalanus macrurus</u> (32%)	1 whale nearby; several feeding whales seen from aircraft previous day
Bradstreet et al. 1987								
6. King Point, Yukon Coast 69°05'N 137°47'W	5 Sep 86	14	776	1543	3	Copepods (91%)	<u>Limnocalanus macrurus</u> (86X)	About 12 whales observed from ship; probably feeding
7. King Point, Yukon Coast 69°08'N 137°38'W	5 Sep 86	21	455	771	14	Copepods (61X) Euphausiids (20X)	<u>Limnocalanus macrurus</u> (26X) <u>Calanus hyperboreus</u> (18%)	3 whales observed from ship possibly feeding
8. North of Tuktoyaktuk 70°42'N 132°53'W	30 Aug 86	49	369	--	--	Copepods (85%)	<u>Calanus hyperboreus</u> (76X)	Whales observed within 50 m of ship
9. Off E. Tuk. Penin. 70°44'N 130°46'W	3 Sep 86	36	527	--	--	Copepods (87X)	<u>Calanus hyperboreus</u> (69%)	3 whales observed within 500 m of ship

Table 68. Concluded.

Location	Date	Water Depth (m)	Zooplankton						Bowheads
			Biomass (mg/m <sup>3</sup> )		Depth of Max. Biomass ( m )	Dominant Zooplankters			
			Mean	Maximum		Taxa (%)	Species (%)		
Bradstreet and Fissel (1986)									
10. Off Kay Pt., Yukon Coast. 69°27'N 138°04'W	27 Aug 85	64	288	1098	8	Copepods (92%)	<u>Limnocalanus macrurus</u> (77%)	Observed from boat	
11. Off King Pt., Yukon Coast. 69°05'N 137°47'W	28 Aug 85	12	n/a	2142	1	Copepods (99x)	<u>Limnocalanus macrurus</u> (97%)	Observed from boat; 1 was surface feeding	
12. Off King Pt., Yukon Coast. 69°08'N 138°00'W	29 Aug 85	21	836	1203	9	Copepods (94%)	<u>Limnocalanus macrurus</u> (88%)	Observed water-column feeding from boat	
13. Off Kay Pt., Yukon Coast. 69°16'N 138°16'W	29 Aug 85	25	n/a	2294 693	8 1	Copepods (98%)	<u>Limnocalanus macrurus</u> (84%)	Observed some water-column feeding and some surface feeding from boat	
Griffiths and Buchanan (1982)									
14. Off Richards Island, Mackenzie Delta 70°00'N 135°43'W	18-19 Aug 81	26	n/a	886 216	15 0	Copepods (79%) ( 7 0 % )	<u>Calanus hyperboreus</u>	30 whalea observed surface feeding (aircraft and boat observations)	

\* echosounder not functioning.

necessitate feeding in higher prey concentrations at other times. Most of our data on zooplankton near feeding whales concern **subadult** animals feeding in **nearshore** areas. Theoretical estimates of minimum prey requirements developed in the '**Energetics**' section (Table 66) show that **subadults** and an average **non-calf** bowhead would have to feed in similar concentrations of **zooplankton**. Thus, the following discussion could **apply** to an average non-calf bowhead as well as a **subadult**.

The maximum biomass available at bowhead feeding locations averaged  $2.0 \pm \text{s.d. } 0.7 \text{ g/m}^3$ . This average represents **zooplankton** biomass at the depth of maximum biomass at feeding locations within the present study area and in the Canadian Beaufort Sea. (**Biomasses** at feeding locations in the Eastern Alaskan and Canadian Beaufort Sea were similar and pooling was warranted.) The mean is based on only those stations where whales showed definite evidence of feeding behavior at the time of zooplankton sampling (locations 1-3, 6, 10-13 on Table 68).

There is good justification for using the biomass within the densest zooplankton layer at each station rather than the mean biomass over some wider range of depths. (1) Bowheads must feed at locations with higher-than-average **biomasses** of **zooplankton** in order to meet their energetic requirements, and presumably optimize the energetic return from their feeding effort by feeding at the depth with maximum food availability. (2) We did not know and probably did not sample at the precise locations **where** whales fed. (3) Even a short horizontal tow of **10-min** duration integrates data from locations with higher and lower biomass, and underestimates the maximum biomass available to whales. (4) **Euphausiids** formed a substantial proportion of food items in **stomachs** of **bowheads** harvested at **Kaktovik** (Lowry and Frost 1984; Lowry et al. 1987) but were relatively rare in our samples; our estimates of food availability are based mainly on biomass of copepods and probably underestimate **euphausiids**. Thus, even the mean of the maximum **biomasses** at each station ( $2 \text{ g/m}^3$ ) probably underestimates the biomass of zooplankton **available** to feeding whales.

It is noteworthy that the mean of the maximum **biomasses** available at feeding sites,  $2 \text{ g/m}^3$ , is similar to the theoretical food requirements of **bowheads** computed using theoretical annual food requirements, 16 h/d of feeding for 130 d in summer, and consumption during the rest of the year equivalent to 30% of daily maintenance requirements (Table 66, p. 444). Such a correspondence between theoretical food requirements and food availability at actual feeding sites has also been found for **rorquals** (Lockyer 1981) and gray whales (Thomson and Martin 1984).

If  $2 \text{ g/m}^3$  is representative of the mean biomass associated with feeding whales, then we can use the **hydroacoustic data** to calculate a theoretical feeding threshold, i.e. the minimum biomass at which **bowheads** could feed and still feed in a mean biomass of  $2 \text{ g/m}^3$ . The **hydroacoustic data** from the **broad-scale** transects provide **information** about the frequency of various prey abundances in the Eastern Alaskan Beaufort Sea. Only a **low** proportion of the water in the top 50 m of the water column over the **continental** shelf contained in excess of  $2.0 \text{ g/m}^3$ —about 0.5% in 1985 and 0.1% in 1986 (Table 69, column B). To consume a mean of  $2.0 \text{ g/m}^3$ , a **subadult** bowhead feeding in our study area during September 1985 would have had to feed at locations where **zooplankton** biomass was at least  $1.25 \text{ g/m}^3$ ; the mean **zooplankton** biomass in

Table 69. Frequency of occurrence of various zooplankton biomasses as estimated from hydroacoustic data recorded during broad scale surveys in 1985 and 1986. Biomasses in transect segments are tabulated in 0.-25 g/m<sup>3</sup> intervals. In 1985 each segment was about 250 m long and 2 m thick. In 1986 segments were about 365 m long and 1 m thick. Only those segments below depth 6 m (1985) or 4 m (1986) and above depth 50 m are considered.

A. Range of Zooplankton Biomass (g/m <sup>3</sup> )	B. Frequency of Biomass in This Range (# segments)		C. Mean Biomass in This and All Greater Ranges (g/m <sup>3</sup> )		D. Percent of Total Biomass Over Shelf in This Range .		Total Biomass on Shelf, Eastern Alaskan Beaufort Sea			
							E. In Range (MT)		F. Cumulative (MT)	
	1985	1986	1985	1986	1985	1986	1985	1986	1985	1986
<b>0.00 -0.25</b>	3617	13969	0.249	0.270	35.03	28.32	23,764	22,548	67,831	<b>79,630</b>
<b>0.25-0.50</b>	1119	6630	0.517	0.477	29.51	35.95	20,015	28,623	44,067	57,082
<b>0.50-0.75</b>	322	1788	0.882	0.782	14.77	<b>16.77</b>	10,017	13,355	24,052	28,459
<b>0.75-1.00</b>	100	600	1.323	1.079	<b>6.54</b>	<b>8.14</b>	4,438	6,481	14,034	15,104
<b>1.00-1.25</b>	27	246	1.766	1.333	<b>2.26</b>	<b>4.27</b>	<b>1,536</b>	3,403	9,596	8,623
1.25 -1.50	24	144	<b>1.997<sup>b</sup></b>	<b>1.542</b>	<b>2.49</b>	<b>3.09</b>	1,686	2,462	<b>8,060<sup>c</sup></b>	5,220
<b>1.50 -1.75</b>	10	<b>84</b>	<b>2.281</b>	1.746	<b>1.23</b>	<b>2.12</b>	832	1,692	6,373	2,759
<b>1.75-2.00</b>	<b>17</b>	<b>30</b>	2.434	<b>2.025<sup>b</sup></b>	<b>2.41</b>	<b>0.88</b>	1,638	697	5,42	<b>1,067<sup>c</sup></b>
2.00-2.25	8	<b>7</b>	2.794	2.456	<b>1.32</b>	<b>0.23</b>	898	183	3,904	370
2.25 -2.50	4	<b>1</b>	<b>3.057</b>	2.974	<b>0.71</b>	<b>0.04</b>	484	30	3,006	186
2.50-2.75	<b>1</b>	<b>1</b>	3.248	<b>3.123</b>	<b>0.19</b>	<b>0.04</b>	<b>132</b>	32	<b>2,521</b>	157
2.75-3.00	4	<b>0.</b>	3.298	<b>3.307</b>	<b>0.86</b>	<b>0.00</b>	584	0	2,390	<b>124</b>
3.00-3.25	6	<b>1</b>	3.489	3.307	<b>1.45</b>	<b>0.005</b>	985	38	1,806	124
3.25-3.50	1	<b>1</b>	<b>3.967</b>	3.445	<b>0.27</b>	<b>0.05</b>	181	42	821	86
3.50-3.75	0	<b>1</b>	<b>4.126</b>	3.580	<b>0.00</b>	<b>0.06</b>	0	45	641	45
<b>3.75 -4.00</b>	1		<b>4.126</b>		<b>0.30</b>	-	200	-	641	
4.00-4.25	<b>1</b>		4.255		<b>0.31</b>	-	207		440	
4.25-4.50	0 <sup>a</sup>		4.501		<b>0.00</b>	-	<b>0</b>		233	
<b>4.50-4.75</b>	<b>1</b>		<b>4.501</b>		<b>0.34</b>	-	<b>233</b>		233	
<b>5,26323,503</b>					100	100	67,831a	79,630a		

<sup>a</sup> From Table 67.

<sup>b</sup> This is the mean biomass in all transect segments that contained a biomass >1.25 g/m<sup>3</sup> (1985) or >1.75 g/m<sup>3</sup> (1986).

<sup>c</sup> This is the estimated total amount of zooplankton occurring in water where the biomass was >1.25 g/m<sup>3</sup> (1985) or >1.75 g/m<sup>3</sup> (1986).

broad-scale **hydroacoustic** transect segments where the **actual** biomass was  $\geq 1.25$  g/m<sup>3</sup> was 2.0 g/m<sup>3</sup> (Table 69, column C). In September 1986 the corresponding theoretical threshold **would** have been about 1.75 g/m<sup>3</sup> (Table 69C). The higher calculated threshold in 1986 resulted from a lower percentage frequency of very high biomass along the broad-scale transects sampled in 1986 (Table 69B).

In September 1985, bowheads **could** have fed on a mean **zooplankton** biomass of 2 g/m<sup>3</sup> by feeding **in** concentrations of 1.25 g/m<sup>3</sup> or greater, and in 1986 by feeding in concentrations of 1.75 g/m<sup>3</sup> or greater. At the majority of locations, such **concentrations** of zooplankton were not present at any depth in the water column. Along the broad-scale oceanographic transects over the continental shelf in September 1985; only 53 of 330 (16%). 2-rein segments of transect (each about 250 m **long**) contained a biomass  $>1.25$  g/m<sup>3</sup> at some **depth**. Along the 1986 transects, only 30 of the 648 (5%) 2-rein segments (each about 365 m **long**) contained  $>1.75$  g/m<sup>3</sup> at some **depth**. (This analysis is based on the data summarized in Figures 99 and 100 on p. 220-222.) Thus about 5% (1986) to **16%** (1985) of the area of the continental shelf (depth <200 m) within our study *area may* have provided suitable **feeding** habitat for **bowhead** whales at any one **time**.

**Within** the continental **shelf** portion of the study area, the quantity of zooplankton occurring **in** such concentrations was not. large. In 1985, 12% of total **zooplankton** biomass (8060 of the 68,000 MT) was **in** the broad-scale transect segments (each approx. 250 m horizontally by 2 m vertically) that contained  $>1.25$  g/m<sup>3</sup> (Table 69, column F). In 1986, only **1.3%** of total zooplankton biomass (about 1100 of 80,000 MT) was **in** the broad-scale transect segments (each **approx.** 365 m by 1 m) that contained  $>1.75$  g/m<sup>3</sup>. **Thus, at any one time** only about **1.3%** (1986) to 12% (1985) of the zooplankton over the continental shelf was sufficiently concentrated to permit efficient feeding by **bowheads**.

The total **biomass** of about 75,000 MT of **zooplankton** over the continental shelf **within** the study area **is** roughly **18%** of the annual food requirements of the Western Arctic bowhead population (421,000 MT for a population of 4417 individuals from Table 65 on p. 443). However, our evidence suggests that **only** about 1100 MT (1986) or 8060. MT (1985) of this **zooplankton** was sufficiently concentrated to support efficient feeding at any one **time**. These amounts represent only about 0.3% and **2%** of the total annual requirement of 4417 bowhead whales, and even lower percentages **if** there are about 7200 bowheads as **is** now suspected (**I.W.C. in press**).

**Zooplankton** patches are transitory and constantly in the process of forming and dispersing. Thus, over the several-week period when the study area is used by bowheads, more than the 1100 to 8000 MT of **zooplankton** found in patches at any one time could be available in a concentrated form to bowheads. The rate at **which zooplankters** may aggregate into patches in the study area **in** late summer is unknown. Thus, there is no way to estimate how much more concentrated prey might become available later in the season if the initial patches containing 1100-8000 MT were consumed by bowheads and other consumers.



The above calculations obviously provide **only** a rough estimate of feeding potential within the **study area**. The **hydroacoustic** surveys provide only rough estimates of zooplankton biomass. The **250 x 2 m** or **365 x 1 m** resolution **cells** within which biomass was averaged probably exceed the dimensions of some dense **zooplankton** patches. This would **result** in underestimation of biomass at the locations of maximum **zooplankton** concentration (**Crowley 1977**). The net tows used to calibrate the **hydroacoustic** system probably underestimated zooplankton biomass in some areas, especially where fast-swimming organisms like **euphausiids** were concentrated. In addition, the limited **hydroacoustic** coverage (**2** broad-scale transects in 1985; **4** in 1986) may have under-sampled areas of high zooplankton abundance. However, even allowing for the likelihood that we underestimated the amount of concentrated prey available in 1985 (estimated as **<2%** of annual population requirements) and especially in 1986 (**<0.3%**), the continental **shelf** portion of the study area did not contain, at any one time, more than a small percentage of the annual Population requirement for densely concentrated prey. Additional **investigation** would be needed to determine whether the rate of formation of prey aggregations is rapid enough to alter this conclusion appreciably when the **full** several-week period of utilization of the study area by **bowheads** is considered.

#### Zooplankton Consumption in the Study Area by the Bowhead Population

Utilization of the study area by bowhead whales "was **low** in 1985 and moderate in 1986. "The main summer **feeding** range prior to the onset of **active** westward migration did **not** extend into Alaskan waters in 1985, but extended into the southeastern corner of the study area in 1986. In both years, **bowheads** fed in the **continental shelf** portion of the study area as they were migrating west in late September. **Total** usage of the study area in the autumn of 1985 was on the order of 4200 whale-days. The corresponding figure for 1986 was 12,950 whale-days (see p. 304-309).

The average bowhead weighs about 37.7 MT and has a mouth area of about **3.9 m<sup>2</sup>** (Table 58, p. 425). If it feeds for 12 h/day at a speed of **5 km/h** (see **'Energetics'**, 444-445) in **zooplankton** concentrations averaging **2 g/m<sup>3</sup>**, it will consume about 468 kg/d. If all whales using the study area in 1986 fed at this rate, about 6061 MT of **zooplankton**, or 1.4% of the estimated annual requirement of 421,000 MT for a population of 4417 **bowheads**, would have been consumed (i.e. 12,950 whale-days of feeding at 468 kg/whale-d). As discussed above, the **hydroacoustic** data suggested that, at any one time, only about 1100 MT of **zooplankton** occurred in water where the **zooplankton** biomass exceeded the calculated **1.75 g/m<sup>3</sup>** feeding threshold in 1986 (Table 691?). The total biomass of zooplankton that could form dense patches during the several weeks of migration is unknown; it might exceed 6061 MT even if no more than 1100 MT were in dense patches at any one time. The estimated total consumption of 6061 MT in 1986 represents 8% of the **zooplankton** that occurred over the **shelf** within the study area.

Utilization of the study area was much lower in 1985 (about 4200 **whale-d**) than in 1986. If all whales fed at the above daily rate, then about 1966 MT of **zooplankton** would have been consumed (4200 whale-d times 468 kg/whale-d). This 1966 MT figure is substantially lower than the 8060 MT of **zooplankton** that was estimated to occur in water where, at any one time, **zooplankton** biomass exceeded the estimated **1.25 g/m<sup>3</sup>** feeding threshold in 1985.

Thus , based on the observed numbers of bowheads **in** the study area and reasonable assumptions about their feeding rates, food **intake in** the study area could have **totalled** about 6000 MT of **zooplankton** in 1986 and 2000 MT in 1985. If so, consumption in the study area represented about 1.4% (1986) or 0.5% (1985) of the estimated 421,000 MT of **zooplankton** required by a population of 4417 bowheads in one year. If our estimates of the weights of bowheads are too high, which is a possibility, then energetic requirements for the population may be lower than the 421,000 MT figure (see '**Energetics**', p. 440), and feeding in the Eastern Alaskan Beaufort Sea would provide a slightly higher proportion of population requirements. On the other hand, **if** we assume a population size of 7200 bowheads rather than 4417, the percentage of **annual** food requirements obtained **in** the study area might be even lower than our 1.4% (1986) or 0.5% (1985) **estimates.**

No reasonable combination of Uncertainties and adjustments seems large enough to add more than a very few percentage points to the '**1.4%** and 0.5% of annual population requirements' figures. Thus, we conclude that the Western Arctic bowhead population consumed only a **small** percentage of its annual food requirement in the study area **in** the late summer-autumn periods of 1985 and 1986.

#### **Zooplankton Consumption in the Study Area by Individual Bowheads**

Feeding within the Eastern Alaskan Beaufort Sea might **be** important to some individual **whales** even **if it** contributes little of the food consumed by the entire **bowhead** population during the year. Groups of, bowheads have sometimes been seen for several days at specific locations within the official study area (LGL and Arctic Sciences 1985; this study). Before 1986 there **was no** proof that, within our study area, the same individual bowheads remained **at** feeding locations on subsequent days. However, **we** found that some individually recognizable bowheads did remain from day to day **in the** feeding area **off** the Kongakut Delta (Table 41, p. 322). Similarly, some recognizable individuals recur over periods of many days at various feeding locations **in** the Canadian Beaufort Sea, including the Yukon coast near Komakuk--**just** east of our study area (Davis et al. 1983, 1986a,b; this study). The average and maximum documented **residence** times near Komakuk **in** 1985-86 were 7.6 and 16 days (see '**Bowheads**', p. 323), but such values are inherently underestimates.

Thus, when feeding bowheads are seen in an area over a period of several days, at least before active migration begins, **it is** very likely that specific whales are remaining **in** the area from day to day. These individual **bowheads** consume a higher fraction of their annual energy **intake in** the study area than does the population as a whole. .

In 1985, there was no evidence that any individual bowheads fed in the study area for long enough to acquire a significant "fraction of their **annual** energy intake. Bowheads were virtually absent **until** active migration began, and there were no between-day **resightings** of individually recognizable whales within the study area. In 1986, a small number of **bowheads** (perhaps 50, mostly **subadults**) **did** feed in the SE corner of the study area for several days in early September; they then left that specific feeding area, but we do not know whether they left the study area as a whole. It is not known how long those

whales fed within the study area; however, their residence times along the coast west of 141°W may have been as much as 10 days (Fig. 127, p. 290).

A subadult whale that fed within the study area for 10 days could consume a significant amount of food, although only a small fraction of the total annual requirement according to our data. An average subadult has a mouth area of 2.7 m<sup>2</sup> (Table 58, p. 425). If it feeds for 16 h/d at a speed of 5 km/h in zooplankton concentrations of 2 g/m<sup>3</sup>, it would consume 432 kg/d. In 10 d it would consume 4.3 MT. Total annual requirements of an average subadult are 71 MT/yr (Table 64, p. 440). Given the above assumptions, a subadult could consume 6% of its annual requirements if it fed in the study area for 10 days. Actual consumption might be somewhat higher because peak abundances of zooplankton were probably underestimated. On the other hand, our assumptions of feeding for 16 h/d, at 5 km/h, and for 10 d may all be somewhat overestimated. If subadult bowheads weigh less than we estimated (see 'Energetics', p. 441), total annual requirements would be lower and consumption within the study area would represent a larger proportion of total annual requirements. If weights are 25% less than we calculated, consumption in 10 d of feeding might represent 8% rather than 6% of annual requirements.

There is no strong evidence that any individual bowheads feed in the study area for more than 10 days in some years, but this is a possibility. Our two years of study were years of below-average (1985) and below-maximum (1986) utilization of the study area for the population as a whole (p. 365-366). It is also probable that some individual whales find food concentrations considerably exceeding the 2 g/m<sup>3</sup> figure used in our calculations. For example, 10 days of feeding on 4 g/m<sup>3</sup> or 15 days of feeding on 2.7 g/m<sup>3</sup> might provide 12-16% of annual requirements rather than the 6-8% calculated above. Thus, although most individual bowheads obtain little of their annual food requirement in the study area, it is possible that a few individuals do obtain significant amounts of food there in certain years.

#### Summary of Energetic Importance of Study Area to Bowheads

We conclude that the Western Arctic bowhead population acquired very little of its total annual food requirements from the Eastern Alaskan Beaufort Sea during the late summer and autumn of 1985 or 1986. This conclusion is reached by each of two lines of argument.

1. Consumption by Bowhead Population: The observed utilization of the study area by bowheads in 1985 and 1986 was about 4200 and 13,000 whale-days, respectively. Based on these figures, on the observed zooplankton biomass at whale feeding sites (average of 2 g/m<sup>3</sup> at depth of maximum biomass), and on reasonable assumptions about feeding rate, food intake in the study area in 1985 and 1986 could have totalled about 2000 and 6000 MT, respectively. These estimates are only 0.5% and 1.4% of the estimated annual food requirement of 4417 bowheads.
2. Consumption by Individuals: Different bowheads feed in the study area for variable periods. Some may have been present for as much as 10 days in 1986. Even these individuals probably acquired only about 6-8% of their annual energy needs within the study area.

The above two arguments, taken together, indicate that the null hypothesis posed at the start of this study should be accepted, at least for the population as a whole:

**'Food resources consumed in the Eastern Alaskan Beaufort Sea do not contribute significantly to the annual energy requirements of the Western Arctic bowhead stock.'**

For years of low utilization (like 1985) and probably for those of moderate utilization (like 1986), the same conclusions can be drawn for most if not all individual bowheads. There is little information about how long certain whales may feed in the study area in some other years. However, there is no evidence that many feed there for longer than 10 days. . Ten days of feeding at a location with the zooplankton biomasses that have been found near feeding bowheads apparently supplies only a small percentage of the annual energy requirement of an individual bowhead.

#### Bowhead Feeding Areas in the Eastern Alaskan Beaufort Sea

During this study, significant numbers of bowheads were seen feeding in the middle shelf region off Kaktovik and off Demarcation Bay, and along the coast off the Kongakut Delta. We also observed much feeding along the Yukon coast near Komakuk, just to the east of the official study area. The following sections integrate our evidence about feeding activities, zooplankton and the physical oceanography of those areas.

#### Feeding in the Mid-Shelf Area

The only part of our official study area where many bowheads were known to feed during 1985 was in the mid-shelf area north and northeast of Kaktovik at about the 50 m contour in late September (Fig. 117, 118; p. 278, 279). Numerous bowheads, some believed to be feeding, were seen at the same location on 21-26 September 1984; feeding bowheads had not been noticed in this area before 1984 (Fig. 109, p. 260). In late September 1986, bowheads were also concentrated at or shoreward of the 50 m contour across most of the study area (Fig. 126, p. 289). The whales seen in these areas were traveling and feeding. Almost all of the apparent feeding in the mid-shelf area in late September of 1985-86 was deep enough in the water column that the whales were visible only when they surfaced to breathe. In both 1985 and 1986, most of the whales observed in the mid-shelf area in late September were adults (some with calves) or large subadults; there were few small subadults (Fig. 130, 132; p. 313, 315). Despite the fact that many of these whales were individually recognizable, none were re-photographed at the same locations on subsequent days. This suggests that the whales in the mid-shelf area were not lingering for long in any one area. These whales were apparently feeding intermittently while traveling.

In 1985, our Boat Transect 1 passed through the mid-shelf area off Kaktovik in early September, about 2 weeks before many whales began to feed there. However, by late September, oceanographic conditions there had undoubtedly changed dramatically. Strong westerly winds in mid September mixed the water column and brought much pack ice into the area. Also as a result of

these winds, the area was no longer near the southern edge of the Mackenzie Bay water.

In 1986, sampling of the broad-scale transects was also completed before many **whales** began to travel west through the mid-shelf region. There was again a period of **strong westwinds** between the end of sampling and the period when **whales became** common. Because these winds did not bring much ice onto the continental shelf part of our study area, surface conditions **could** still be monitored by satellite in late September 1986 (Fig. 37, p. 81). The surface water throughout the **study** area was **cold** at this time (Fig. 373). The satellite imagery provided no information about subsurface conditions. **However**, the shoreward edge of a strong subsurface intrusion of Bering Sea water **was near** the 50 m contour in early-mid September (Fig. 49, p. 96) and in mid October, and was probably at a similar location in **late** September. At the time of boat-based sampling, there was no clear evidence that zooplankton was concentrated at the edge of (or in) the Bering Sea water.

In early-mid September of 1985-86, zooplankton abundance in surface waters over the shelf was very low (Table 25, p. 246). Conditions near the surface may have been more suitable for **zooplankton** in late September of both years, given (a) the **mixing** caused by the strong winds, and (b) the eastward retreat of the Mackenzie plume. However, results from sampling on 18 September 1985, after a period of strong west winds, indicated that a **pycnocline**, although **less** clearly **defined**, was **still present**. Even then, zooplankton biomass remained **lower** above than below the **pycnocline** (Griffiths et al. 1986, p. 135). The probable scarcity of **zooplankton** near the surface would account for the predominance of water-column feeding over near-surface feeding in the mid-shelf area during both years.

We studied **zooplankton** extensively over the **mid-shelf** during both 1985 and 1986, but not **at** times and places when bowheads were present. The dominant copepods over the mid-shelf were Calanus hyperboreus and C. glacialis. These two species were also the dominant copepods *in* stomachs of whales harvested at Kaktovik (Lowry and Frost 1984). We have no specific information **about** the capture locations of the whales that contained Calanus. However, many of the **whales** taken near Kaktovik are taken far enough offshore **to** be in waters where Calanus dominates; of 36 locations near Kaktovik where bowheads were **struck**, 21 were mapped as being north of the 18 m contour (Anon. 1986, p. 51).

**Hydroacoustic** surveys in the mid-shelf area during early-mid September showed **scattered** patches of concentrated **zooplankton** in both years. We have no information about the presence or locations of such **patches** in late September, but suspect that patches were still present. Some of these concentrations were near the **pycnocline**, especially in 1985. Others were **closer to** the bottom, especially in 1986 (Fig. 99, 100, p. 220-222). Aside from **those** cases, no physical mechanism was identified to **explain** the occurrence of most zooplankton patches found **over** the middle shelf.

We expect that migrating bowheads feed opportunistically in at least some of the **zooplankton patches** that they encounter while traveling west over the **middle** shelf. The hypothesized opportunistic nature of this feeding would be consistent with the variable feeding locations in this area (Fig. 109, p.

2 6 0the mainly unknown physical explanations for concentrations of zooplankton there, and the variable ice conditions and migration timing.

### Feeding off the Kongakut Delta

About 50 bowheads, **mainly subadults**, fed below the surface in shallow water near the **Kongakut** Delta for a few days in early September 1986. **Whales** did not feed there in 1985. **Ljungblad et al.** (1983, 1986a) did not report feeding bowheads close to shore near the **Kongakut** Delta in 1979-84, but did observe feeding **close** to shore just east of Demarcation Bay in 1979. Johnson (1984) **saw many** bowheads close to shore near the **Kongakut** Delta **and** elsewhere to **the east** and west on 22 September 1982; he suspected that some of these whales were feeding (**S.R. Johnson, pers. comm.**).

In 1986, a nearshore band of **turbid** water was present in the SE portion of the study area (p. **62 ff, 102 ff**). Off the **Kongakut** Delta this band was one to several kilometers **wide**. Beneath the thin turbid surface layer, the **pycnocline** was stronger and the subsurface water was colder and more saline than in waters slightly farther offshore. Fronts and eddies were common at the edges of this nearshore band. Intense horizontal gradients in temperature and salinity were present in subsurface **waters** at depths <15 m (p. 112-113).

Zooplankton biomass was extremely high in thin subsurface layers of zooplankton at the shallow (**11-22 m**) sampling stations near feeding whales (**Table 68, locations 1-3**). **Zooplankton** biomass was far lower at control stations located seaward of the nearshore band of turbid water, where whales were not feeding (Table 13, p. **191**). The patches of concentrated zooplankton and the whales that fed on them were associated with intense horizontal gradients in temperature and salinity. The small **copepod** **Limnocalanus macrurus** was the dominant **zooplankter** near the feeding whales. The major **difference** between the **zooplankton** near feeding whales and at the corresponding control stations was the presence of much larger numbers of **L. macrurus** near the whales.

Sampling was not conducted off the **Kongakut** Delta in 1985, so it is **not** known if there was an equally high abundance of **Limnocalanus** or other zooplankton there in 1985. In 1986, **zooplankton biomass** in nearshore areas farther west was high relative to that in offshore waters, but not as high as that just off the **Kongakut River or Komakuk** (Table 68, 70). Thus, there may have been an east-to-west decline in zooplankton biomass along the coast in 1986. The western edge of the zone of high zooplankton biomass extended into the SE 'corner' of the official study area in 1986 but perhaps did not do so in 1985. However, our main evidence for lower **zooplankton** biomass west of the Alaska/Yukon border in 1985 was the lack of feeding whales there--admittedly a rather circular argument.

A possible 'explanation' for the hypothesized between-year difference in nearshore **zooplankton** abundance in the SE corner of the study area is that the strong horizontal gradients in temperature and salinity may not have existed there in 1985 (see 'Water Masses'; p. 131). To **confirm** this, additional sampling during late summers with and without the nearshore band of turbid water, and with and without feeding **bowheads**, would be necessary. In a year when **zooplankton** is abundant along the **coast**, repeated sampling on a

Table 70. Mean biomass and percent of **total** biomass represented by major **taxa and** species in the upper **50 m** of the water **column** in the **eastern Alaskan Beaufort Sea** in 1985 and 1986. Only those samples that were **identified to specific level-are considered.**

	Nearshore In Sept.		Inner Shelf In Sept.		Outer Shelf In Sept.		October 1986		Whale Feeding Areas	Control Areas
	1985	1986	1985	1986	1985	1986	55 m	>1500 m		
<b>Total Biomass (mg/m<sup>3</sup>)</b>	487	296	209	170	133	43	90	170	586	86
<b>No. Oblique tows</b>	1	8	4	3	4	7	2	3	6	5
Percent of Total Biomass										
Copepods	83*0	84.2	75.6	57.1	77.1	20.1	36.8	19.3	86.6	42.3
<b>Mysids</b>	3.6	0.7	0.1	0.3	0.0	0.0	0.0	0.0	5.6	2.0
Euphausiids	4.4	0.2	1.9	0.7	0.2	0.0	0.4	1.0	0.0	0.4
Gelatinous zooplankton	5.2	4*0	13.3	12.6	13.5	36.6	55.4	64.9	4.0	23.6
<b>Chaetognaths</b>	2.0	0.4	3.4	4.4	4.1	11.8	4.8	10.5	0 . 4	2.3
<u><b>Calanus hyperboreus</b></u>	17.1	7.0	49.3	20.9	57.4	11.9	3.7	1.8	0.2	3.7
<u><b>Calanus glacialis</b></u>	2.4	31.7	18.1	34.3	12.6	7.2	32.1	14.3	0.5	7.1
<u><b>Limnocalanus macrurus</b></u>	40.1	44.2	4.6	1.3	0.2	0.3	0.0	0.0	84.2	29.4

fine-scale basis **would** be desirable in order to understand the dynamics of Limnocalanus and other prey concentrations.

#### Feeding Near Komakuk

Bowheads heavily utilized the Komakuk section of the Yukon coast between the study area and Herschel Island from mid August to late September of 1985 and 1986. Feeding bowheads were observed in the shallow ice-free water in this area (p. 273 ff, 284 ff). In 1985 this represented the westernmost edge of the summer feeding range. In 1986, the bowhead concentration extended farther west, to the Kongakut Delta area. Bowheads had also been present near Komakuk during the late summer of 1984, although not in 1983 (Richardson et al. 1985a, 1987).

The whales found off Komakuk in 1984-86 were mainly subadults similar in size to those off the Kongakut Delta (p. 313 ff). These whales sometimes fed at and near the surface--occasionally in echelon formation--but more often fed below the surface (p. 332-335). No detailed zooplankton or physical oceanography work was done near Komakuk before 1986. In 1985, satellite imagery showed the Komakuk area to be the eastern end of a nearshore zone of cold water that extended across our study area (p. 53). Salinity and nutrient profiles obtained farther west suggested that the cold nearshore band present in 1985 was partly a result of upwelling (p. 90, 390). However, coastal upwelling near the Alaska/Yukon border may not lead to greatly increased zooplankton biomasses given the slow growth rates of zooplankters relative to the typical durations of these upwelling events. Thus, the reasons for the concentrations of bowheads near Komakuk cannot be determined with certainty.

In 1986, a narrow band of freshened, turbid surface water (1 m thick) was found close to shore off Clarence Lagoon, near Komakuk. Bowheads had been feeding there the day before our oceanographic sampling. A horizontal tow through colder and more saline water at 8 m depth yielded the highest biomass of any tow during this study, nearly 4 g/m<sup>3</sup>, mainly Limnocalanus macrurus and other copepods (Table 68, location 5). A hydroacoustic transect showed a dense but thin layer of zooplankton at mid-water (Fig. 86, p. 196). Why most bowheads had left this area by the time of sampling is not known; copepods were still abundant.

At a station, just west of Herschel Island, the physical oceanographic regime differed from that off Clarence Lagoon and the Kongakut River. A band of turbid Mackenzie Bay water was found 2 to 8 km from shore. The subsurface water farther offshore was colder and more saline than that at the nearshore stations--the reverse of the situation farther west. Zooplankton biomass was low at a nearshore station where feeding whales had been observed the day before (Table 68, location 4). No patches of concentrated zooplankton were found by the echosounder (Fig. 83, p. 190). This site may have been abandoned by feeding whales because of the low zooplankton biomass.

Subadult bowheads were present in the Komakuk area for several weeks in both 1985 and 1986. Some individual bowheads recurred in the Komakuk area for as much as 16 days, and some returned to this area in 1986 after having been there in 1985. Thus, conditions must have been favorable. The dense layer of copepods near Clarence Lagoon when we sampled there in 1986 appeared to be a



very **suitable location** for feeding below the **surface**, even though bowheads **were not** using that particular location when **the** zooplankton sampling was done. We did not find a high biomass of **zooplankton** at the surface at any of our few stations near **Komakuk**. However, we occasionally saw bowheads feeding **at** the surface. Farther **east**, in southern Mackenzie Bay, high biomasses have sometimes been found at the surface when **cold**, saline Arctic Water occurs at the surface (**Bradstreet and Fissel 1986**). The occasional occurrence of surface feeding near **Komakuk** suggests that similar conditions probably occur sporadically near **Komakuk** as well.

**Bowheads** remained off the **Kongakut Delta** for **only** a few days in **early** September 1986, and were absent in 1985. In contrast, **bowheads** remained off **Komakuk** for several weeks in **both** years, and were also present in 1984. Changes in the **physical** oceanographic regime may have been responsible. The intense **gradients** in surface temperature and **turbidity** that had been observed off the **Kongakut Delta** in **early** September 1986 were less evident by 14 September (Fig. 32, 33 vs. 36, p. 71 **ff**). Subsurface properties probably changed as well; if so, this may have eliminated the processes responsible for concentrating **zooplankton** off the **Kongakut Delta** in early September 1986. In contrast, satellite imagery suggested that conditions off **Komakuk** did not change appreciably at least between 6 and 14 September (Fig. 32 vs. 36), and many whales remained off **Komakuk** until about 20 September.

**The Eastern Alaskan Beaufort Sea** is the western edge of the summer feeding range of bowheads. Because the study area is **at the** edge of a variable summer range, feeding **bowheads** apparently occur there in some but not **all** years prior to the onset of the main westward migration. Variable oceanographic conditions probably are responsible. However, aside from the requirement for a high biomass of **zooplankton**, specific conditions causing the main summer feeding area to extend into **Alaska** in some **years** are unknown. When westward migration through the study area begins in **earnest**, feeding becomes more widespread, but may **not** persist for long at any one location.

#### **Species Composition of the Plankton and of Bowhead Prey**

The stomach contents of **bowhead whales** harvested near **Kaktovik** in **early** autumn show that, in **the** study area, bowheads feed **mainly** on **planktonic** animals. Stomachs of virtually **all** bowheads taken **at** Kaktovik contain prey, indicating **that whales** in nearshore and **inner shelf** waters near **Kaktovik** feed frequently (Lowry and Frost 1984; Lowry et al. 1987). The composition of the plankton in the stomachs was quite variable, suggesting that different whales had been feeding in patches of different prey. Sometimes the dominant prey were not dominant **zooplankters** in samples acquired during this study.

**Copepods.**--The species composition of **zooplankton** in the Eastern Alaskan **Beaufort Sea** in September 1985-86 was not **noticeably** different from that elsewhere along **the Beaufort Sea** coast and in **other arctic** regions. Overall, copepods dominated the **zooplankton**. In 1985, **copepods** were the dominant taxon over the inner and outer shelf regions. In 1986, **copepod** biomass decreased with increasing distance from shore, and formed <40% of total biomass over the outer shelf and slope (Table 70).

Copepods were the major food group in stomachs of 7 of 11 bowheads taken near Kaktovik (Lowry and Frost 1984; Lowry et al. 1987). Copepods have also been found to be more abundant in areas where bowheads were feeding than in areas without feeding bowheads; this was true off the Kongakut Delta in early September 1986 (this study) and in the Canadian Beaufort Sea during 1980-81 and 1985-86 (Griffiths and Buchanan 1982; Bradstreet and Fissel 1986; Bradstreet et al. 1987). Copepods are also known to be the predominant food for balaenid (= right) whales in other oceans (e.g. Nemoto 1959; Nemoto and Kawamura 1977; Pivovarov 1979; Mayo et al. 1985; Kenney et al. 1986).

The small copepod Limnocalanus macrurus was abundant in the nearshore zone of the study area in September 1985-86 (Table 70) and was the dominant zooplankton at nearshore locations where bowheads were observed feeding (Table 68). Neither this species nor other small copepods had been observed in bowhead stomachs before 1986. However, in 1986 Lowry et al. (1987) found many L. macrurus in 1 of 2 Kaktovik bowheads with stomach contents. Its absence in bowhead stomachs in previous years probably reflected a low abundance of this species in the particular areas where those whales had been feeding. Our evidence suggests that the low frequency of this species in stomachs of whales harvested near Kaktovik underestimates its importance as a prey item for whales feeding in nearshore areas farther east.

The key to understanding the use of nearshore feeding areas by subadult bowhead whales in some (but not all) years may be the biology of Limnocalanus macrurus. It was the dominant zooplankton at 10 of the 14 bowhead feeding stations for which detailed zooplankton data have been reported (Table 68). Present knowledge of its habits and life history are summarized in the 'Zooplankton and Hydroacoustics' section (p. 204). This species has not been studied in detail in arctic marine waters, and the aspects of its biology and ecology that would cause it to become concentrated in cold, saline nearshore waters in late summer are unknown.

Calanus hyperboreus and C. glacialis are generally the dominant copepods in arctic waters (Grainger 1965, 1975). These large copepods have accounted for most of the biomass of copepods recovered from the stomachs of bowhead whales at Kaktovik and elsewhere (Lowry and Frost 1984; Carroll et al. 1987). They were the dominant copepods near feeding whales off Richards Island and the Tuktoyaktuk Peninsula in the Canadian Beaufort Sea (Table 68, locations 8, 9, 14). These two species, along with euphausiids, may be the major prey of bowheads that feed in offshore waters and along the migration route. In our study area, these two species together were the dominant zooplankters over the inner and outer shelf in 1985, and over the inner shelf in 1986 (Table 70).

We found no large patches of Calanus spp. that were being exploited by bowhead whales. However, bowheads did feed in the mid-shelf area during late September of both 1985 and 1986, after zooplankton sampling ended. The dominant copepods in these areas, at least in early-mid September, were Calanus. About 2 weeks before the arrival of feeding whales in the mid-shelf area off Kaktovik in late September 1985, we found  $>800 \text{ mg/m}^3$  of Calanus spp. in two horizontal tows over water depths of 45 m in the same general area. About  $1200 \text{ mg/m}^3$  of copepods, mainly Calanus, were taken in a horizontal tow at 27 m depth near the same location in mid September 1986. We do not know

whether similar concentrations were still there when bowheads were present during late September.

Euphausiids.--Euphausiids formed a larger proportion of the stomach contents of **eight** bowheads taken near **Kaktovik** (**31%** of volume, Lowry and Frost 1984) than of plankton biomass collected in September during this study (Table 70). Three of four whale stomachs from **Kaktovik** that contained significant amounts of euphausiids were taken in 1979 (Lowry and Frost 1984; Lowry et al. 1987). In September 1985, euphausiids appeared to be most abundant in water depths of 45 m or less; maximum abundances were at water depths of about 13 m, where euphausiids constituted 13 to 17% of total zooplankton biomass in our samples. Euphausiids apparently were far less abundant in the study area in September-October 1986 than in September 1985 (Table 70). However, our sampling did not extend close to the bottom, especially in deep water. If euphausiids concentrated near the bottom, they might have been underestimated by our sampling. Patches of concentrated euphausiids must have existed in our study area, since a whale harvested at Kaktovik in 1986 had consumed mainly euphausiids shortly before its death (Lowry et al. 1987).

In October 1986, euphausiids were quite abundant west of our study area, off Barrow (Fig. 80, p. 184). The two whales harvested at Barrow in fall whose stomach contents were examined both contained mainly euphausiids (Lowry et al. 1978; Lowry and Frost 1984). In 1976, Homer (1981) also found euphausiids to be abundant off Barrow and especially off the Harrison Bay region. Abundance of euphausiids in these regions was far lower in 1977 and 1978. The abundance of euphausiids in the Beaufort Sea may be extremely variable.

in other areas, euphausiids are often found in surface, mid-water or near-bottom swarms (e.g. Sameoto 1976; Falk-Petersen and Kristensen 1985; Nicol 1986; Simard et al. 1986a,b). Even when common, they may be missed by sampling devices because of their patchy distributions or their abundance may be seriously underestimated because many individuals avoid sampling nets (Shulenberger 1980; Wiebe et al. 1982; Dolphin 1987). Over the North Aleutian Shelf, the abundance of euphausiids varies with season, year and location, and is associated with intrusions of oceanic water onto the shelf (Thomson 1987). In that area, euphausiids tend to form dense swarms at mid water or just above the bottom. Similar phenomena may occur in the Beaufort Sea.

When coordinated hydroacoustic surveys and net sampling have been done in areas where euphausiids were abundant, it has been possible to locate and sample euphausiid concentrations. Our failure to find such concentrations with these techniques suggests that concentrations of euphausiids were not common in the Eastern Alaskan Beaufort Sea in the autumns of 1985-86. This conclusion is reinforced by the fact that we did catch numerous euphausiids in the Western Alaskan Beaufort Sea, even without guidance by echosounders, in October 1986. Although this suggests that dense euphausiid concentrations were not common in the Eastern Alaskan Beaufort Sea in 1985-86, it is clear that some bowheads do locate and feed on such concentrations near Kaktovik (Lowry and Frost 1984; Lowry et al. 1987). It is important to note that this prey type is undoubtedly more common in the study area than the zooplankton sampling suggests.

**Mysids.**--One of 11 whales harvested at Kaktovik had been feeding mainly on mysids (Lowry et al. 1987). In the Canadian Beaufort Sea in 1986, mysids were dominant zooplankters near a turbidity front where whales were observed (Bradstreet et al. 1987). Mysids are common along the Beaufort Sea coast (Broad et al. 1980; Griffiths and Dillinger 1981; Homer 1981; Jewett et al. 1984; Bradstreet and Fissel 1986). Mysids can form dense shoals along arctic coasts (Thomson et al. 1978), and dense shoals of mysids would provide good foraging opportunities for whales.

**Gelatinous Zooplankton.**--Soft-bodied zooplankton such as ctenophores and medusae have not been found in bowhead whale stomachs. Although these animals are usually fragile, large concentrations of them would probably be recognizable in stomach contents if the whale were killed shortly after feeding (Lowry and Frost 1984). Gelatinous zooplankton contributed much less than copepods to total zooplankton biomass in Eastern Alaskan waters in 1985-86. They were not abundant at whale feeding locations in nearshore waters. However, they did form the dominant zooplankton group over the outer shelf in 1986 (Table 70). The water content of gelatinous zooplankton is high and their caloric content is low relative to other zooplankters.

Although gelatinous zooplankters are probably not a significant food source for bowheads, these groups are voracious predators and may compete with bowheads for crustacean prey. On the North Aleutian shelf, the presence of a high biomass of gelatinous zooplankton reduced the standing crop of crustacean zooplankton to near zero in late summer (Thomson 1987).

**Summary.**--There are some similarities and some differences between the composition of the zooplankton and the composition of the prey of bowheads harvested at Kaktovik. The abundance of Limnocalanus macrurus in the plankton and in bowhead stomachs varies with year and location. This species may be dominant in the nearshore zone most of the time. However, the extent of the water mass where this species dominates can be quite variable, and the overall importance of L. macrurus in the study area probably varies commensurately. Subadult bowheads sometimes concentrate in shallow nearshore waters in late summer, and L. macrurus is apparently more important as prey for these subadult bowheads than has been demonstrated by analysis of stomach contents.

Bowheads also find and exploit concentrations of Calanus spp. In offshore waters of the Beaufort Sea these are the dominant copepods, whereas in nearshore areas they are less important than Limnocalanus. Based on stomach content and other evidence, Calanus is undoubtedly more important as prey for bowheads than our results from nearshore feeding locations indicate.

Stomach contents show that bowheads sometimes feed, in concentrations of euphausiids and, less commonly, mysids. Both euphausiids and mysids have a propensity to swarm, sometimes near the bottom. Some of the patches that we detected hydroacoustically but did not sample with nets could have contained many euphausiids or mysids. However, these groups apparently were not responsible for the majority of the prey patches identified by echosounding; copepods were the dominant animals in the patches that were sampled with nets. There are indications that euphausiids are more abundant in the Western than the Eastern Alaskan Beaufort Sea.

### Bowhead Feeding in Other Areas

The preceding subsection describes feeding by **Western** Arctic bowheads within a small part of their range and a small part of the year. To evaluate the importance of this feeding in the Eastern Alaskan **Beaufort** Sea, feeding in other areas and periods must be considered. "

#### Feeding on the Summering Grounds

Bowheads feed extensively in the Canadian Beaufort Sea in summer where **they** typically reside for **about 3½-4** months. Energetic calculations by ourselves and others have assumed that bowheads feed throughout this summer period, but no serious attempts have been made to document bowhead distribution or feeding before **late July**. Also, **zooplankton** stocks and energy content in the **Beaufort** Sea are undocumented for the late spring and early summer period. Most early-summer sightings of bowheads have been in the extreme eastern Beaufort Sea and western **Amundsen** Gulf, where open water appears earliest and productivity may be enhanced (**Macdonald et al.** 1987).

In late **July** or early August, many bowheads move onto the continental shelf of the Canadian Beaufort Sea where feeding has been observed or suspected at most locations where bowheads were observed. Concentrations of feeding whales have been observed repeatedly at a number of **locations**. Various authors have speculated" about **hydrographic or** other factors that might concentrate **zooplankton** in these areas. However, actual **zooplankton** biomasses within the Canadian Beaufort Sea have been **reported only** by **Griffiths** and Buchanan (1982), Bradstreet and **Fissel** (1986) and Bradstreet **et al.** (1987).

Feeding in Mackenzie Bay.--Many **subadult** bowheads fed in the shallow waters **of** southern Mackenzie Bay in late August and/or September of 1983-86, although **not** in 1980-82. Bradstreet and **Fissel** (1986) and Bradstreet **et al.** (1987) found that average **zooplankton** biomass in Mackenzie Bay was **low** and similar **to** that in our study area (**Fig. 106**), but that bowheads fed at **locations** where **zooplankton** was concentrated. **Zooplankton** biomasses **at whale** feeding locations in Mackenzie Bay were high and dominated by **Limnocalanus macrurus**--comparable to **our** results **off the Kongakut Delta** in 1986. The reasons for **local** concentrations of **zooplankton** in Mackenzie Bay are not entirely **clear** but may include (1) **upwelling** under east wind **or** local southwest wind conditions, (2) fronts between **cold upwelled** water near the coast vs. warm Mackenzie **plume** water farther offshore, and (3) **pycnoclines** between overlying Mackenzie plume water and" subsurface Arctic Water (Bradstreet and **Fissel** 1986; Bradstreet **et al.** 1987).

In 1983-86, high numbers of **subadult** bowheads fed in shallow waters along the Yukon coast for **1-1½** months of the 4 months they spend in "the Beaufort Sea. It is likely that subadults feed at other locations before and/or after feeding along the Yukon coast. Indeed, during 1980-82 they did **not** feed **along** the Yukon coast at **all**. A few of the **subadults** seen along the Yukon coast in 1984-85 had been farther offshore off the Yukon coast at the corresponding time in 1982 (Davis **et al.** 1986b, p. 170 **ff**). There is **little specific** information about where else in the Canadian Beaufort Sea **subadults** feed. However, some of the **whales** present in most other parts of the **Beaufort** Sea

are **subadults** (Davis et al. 1983, 1986a,b; Cubbage and Calambokidis 1987a,b; this study).

**Feeding of Adult Bowheads.**--The many whales feeding in shallow waters in Mackenzie Bay and near Komakuk included very few adults. Adults were **proportionately** more common farther offshore and in Amundsen Gulf. However, it has not yet been possible to account for the whereabouts of all adult bowheads during summer (Davis et al. 1986b; Cubbage and Calambokidis 1987a). Adult bowheads may feed on concentrations of **zooplankton** that contain a biomass similar to that required by subadults (Table 66, p. 444). However, aerial **photogrammetry** and the isotopic results suggest that **subadult** and **adult** bowheads have different feeding patterns and feed in different areas. The majority of the large bowheads may do most of their **feeding somewhere** other than on the continental shelf of the SE Beaufort Sea. Substantial differences in prey used by subadult and adult bowheads may arise because, in some years, many subadults feed extensively in nearshore waters on small ***Limnocalanus macrurus***, which are virtually absent farther offshore. The diets of adult bowheads feeding in other areas during summer are not known, but probably include **larger** proportions of ***Calanus*** spp. and perhaps **euphausiids**. These kinds of dietary differences could account for some of the observed differences in isotopic composition of adult and subadult tissues (p. 406-410).

The relative amounts of feeding in the Canadian vs. the Eastern Alaskan part of the Beaufort Sea are not known very precisely, but there clearly is much more feeding in the Canadian Beaufort. Most of the Western Arctic bowhead population is in the 'Canadian Beaufort Sea for at least **3½-4** mo. Feeding has been observed to be intensive for at least the last half of this period when they are in the southeastern Beaufort Sea (Würsig et al, 1985a,b, 1986). Bradstreet et al. (1987) estimated that during the **last** 6 weeks of their stay **in part** of southeastern Beaufort Sea during 1986, **subadult bowheads** alone consumed about 10% of total annual requirements for the entire bowhead population. In contrast, most bowheads feed for no more than a few days in the Eastern Alaskan Beaufort Sea, and total consumption by all whales (adults as well as **subadults**) was estimated as <1% (1985) or 1.4% (1986) of total annual population requirements. Only a few individual **subadults** are believed to have consumed as much as 6-8% of their total annual requirements there (p. 459).

#### Feeding During Other Seasons

One of the uncertainties in our energetic analyses is that the amount of feeding outside the main summer range is not known. Table 64.(p. 440) provides estimates of the daily food intake necessary in summer and early autumn under several scenarios, including the possibilities of no winter feeding, minimal winter feeding (10% of **daily** maintenance requirements), and more winter feeding (30% of daily maintenance). Because of the limited utilization of the Eastern Alaskan Beaufort Sea by feeding **bowheads**, this uncertainty about winter feeding has no major effect on our conclusions about the relative importance of feeding in Eastern Alaskan waters. However, the amount of winter feeding affects any evaluation of the importance of **feeding** in the Beaufort Sea as a whole.

The isotopic analyses suggest that **subadult** whales feed to a considerable **extent** somewhere outside the continental shelf of the eastern Beaufort Sea. The **ratio** of C-13 to C-12 in muscle and visceral fat changes considerably between the departure of small **bowheads** from the eastern Beaufort Sea **in fall** and their return to the **Beaufort** Sea in spring (p. 406-410).

In large adult whales, the situation seems different. Based on very limited samples, there is **less** seasonal change in isotopic content of adults than of **subadults**. However, the isotopic content of adults in both spring and autumn was not consistent with that of **zooplankton** from the southeastern **Beaufort** Sea. This **suggests that** adult bowheads feed predominantly in different areas than subadults, or **on different** types of prey, or both. The isotopic data suggest that adult **bowheads** obtain **little** energy from **copepods** and other **taxa** occurring **in** shallow continental **shelf** waters of the Canadian Beaufort Sea. The isotopic content **of zooplankton** from **Amundsen** Gulf and deep waters of the eastern Beaufort Sea, areas where adult bowheads may concentrate in most summers, has not yet been determined.

There is direct evidence, from behavioral observations and stomach contents, that bowheads often feed during **fall** migration and, less commonly, spring migration. Apart from the indirect evidence provided **by** the isotopic data, there is no evidence regarding the occurrence or amount of feeding in winter. There **also** are no data on prey availability in winter, or along most of the spring and fall migration routes during those seasons. The direct evidence for feeding in areas outside the **summer** range is **summarized** below.

Feeding in Fall.--Almost **all** bowheads harvested at Kaktovik in **fall** contain **zooplankton** in their stomachs, and the small number of bowheads taken at Barrow in **fall also** contain prey (Lowry and Frost 1984; Lowry et al., 1987). **Bowheads** that appeared to be **feeding** have been seen at many locations across the **full** width of the Alaskan Beaufort **Sea** in autumn (Ljungblad et al. 1986a). Good feeding opportunities probably occur at least intermittently along the autumn migration route through **the** western Beaufort Sea and northeastern **Chukchi** Sea (Braham et al. 1984; Ray et al. 1984; Lowry and Frost 1984; Ljungblad et al. 1986a). **Euphausiids** are sometimes abundant in the Barrow area, as demonstrated during our sampling in October 1986. The stomachs of two bowheads taken at Barrow in autumn contained **mainly euphausiids** (Lowry et al. 1978; Lowry and Frost 1984).

After passing Barrow in autumn, some bowheads apparently travel west across the northern **Chukchi** Sea to the Herald Shoal area and the northeast coast of Siberia. **No** specific behavioral observations of these **whales** have been reported, but it is suspected that they are feeding (Marquette et al. 1982). Bowheads are present there from late August to early November (mainly Sept-Ott). By **early** November most move southeast toward the Bering Strait (Johnson et al. 1981; Bogoslovskaya et al. 1982; Marquette et al. 1982; Miller et al. 1986).

Feeding in Winter.--The data on winter distribution of Western Arctic bowheads are limited, but indicate that bowheads occupy pack ice and **polynyas** in the northern and central Bering Sea (Bogoslovskaya et al. 1982; Brueggeman 1982; Brueggeman et al. n.d. [1984]; Kibal'chich et al. 1986; Ljungblad 1986). **No** stomach content data or detailed behavioral observations are available for

winter. Ljungblad (1986) reported that most bowheads observed from a large patrol aircraft initially were resting, but dived in response to the aircraft. His observations provided no direct indication of feeding.

There are no data on zooplankton biomass in the winter range during winter. In the Bering Sea, large copepods and other zooplankters overwinter in deep water (>200 m). Adult euphausiids also winter at depths >200 m (Ponomareva 1963). In the absence of data on the diving capabilities of bowheads or on zooplankton biomass and patchiness on the wintering grounds in winter, no direct estimate can be made of the consumption that would be theoretically possible in winter. Some zooplankton patches probably exist, and bowheads probably would--as a minimum--exploit such patches on an opportunistic basis. There is evidence that some other species of baleen whales feed opportunistically in winter, although not as intensively as in summer (e.g. Lockyer 1981; Norris et al. 1983). The isotopic data suggest the possibility that bowheads may feed more intensively in winter than was expected based on data from other baleen whales.

Feeding in Spring.--In the Bering Sea in spring, bowheads are often found near the ice edge (Brueggeman 1982). Productivity at the Bering Sea ice edge is high (Niebauer and Alexander 1985). Whether this enhanced productivity results in enhanced feeding opportunities for vertebrates is uncertain. The Bering Sea ice edge is not heavily used by birds in spring (Divoky 1981). Little is known about possible feeding by bowheads at this time. However, of five bowhead stomachs examined at St. Lawrence Island in spring, three were empty and one nearly so. The fifth stomach was nearly full of epibenthic amphipods. Whalers indicated that observations of apparent feeding behavior and/or presence of food in stomachs are not unusual at St. Lawrence Island (Hazard and Lowry 1984).

Most bowheads taken along the west coast of Alaska in spring have empty or nearly empty stomachs (Johnson et al. 1966; Lowry and Frost 1984; Lowry et al. 1987). This indicates a low frequency of feeding relative to that in our study area in late summer. However, intermittent feeding may still occur in spring; in other species of baleen whale food remains in the stomach only about 8-15 h (Lockyer 1981; Bushuev 1986). At Point Barrow, stomachs examined during spring migration were usually empty or nearly so up to 1984, but in 1985-86 there was considerable feeding on copepods and euphausiids (Carroll et al. 1987; Lowry et al. 1987). In 1985, some bowheads were observed to interrupt their spring migration past Point Barrow to feed either near the bottom or under the shore-fast ice. Bowheads harvested along the ice edge had been feeding mainly on copepods, especially Calanus hyperboreus and C. glacialis, along with euphausiids (Carroll et al. 1987).

There is no information about the occurrence of feeding during spring migration across the Beaufort Sea. This migration occurs through heavy pack ice, prior to the peak of the spring phytoplankton bloom. Stocks of zooplankton are probably low along this route, but no specific information about biomass or patchiness is available.

These observations indicate that some bowheads feed opportunistically during fall and spring migration, including during early spring in the northern Bering Sea. It is reasonable to assume that they feed in winter if



concentrations of food are available. However, the data are insufficient to determine the importance of feeding during migration and winter ~~to~~ the annual energy budget of bowhead whales.

### Potential Oil Industry Effects

Two main concerns have been expressed with respect ~~to~~ potential **oil** industry effects on bowhead whales. One is the possible effect of an accidental oil spill or blowout **on bowheads**. The other is the potential for disturbance by underwater noise or **other** stimuli caused by oil industry activities. **This** section discusses possible effects of oil and disturbance on the accessibility of prey to bowheads feeding in the Eastern Alaskan **Beaufort** Sea. The significance of any direct effects of **oil** or disturbance on bowheads is not considered here. The purpose of this section is to identify ecological linkages related to bowhead feeding that **could** be affected by offshore industrial activities. We do not assess the effects of any specific industrial activity or proposal.

### Effects of Oil **Spills** on Prey Availability\*

Contamination of **zooplankton** by oil could affect bowhead **whales** if zooplankton abundance were reduced significantly by the oil, or if the whales ingested significant amounts of oil-contaminated **zooplankton**, or if bowheads avoided oil-contaminated prey. Many laboratory studies of oil effects on particular **zooplankton** species have been done, including one on the euphausiid **Thysanoessa raschi**, a **major** food source for bowheads in the Alaskan Beaufort Sea (**Fishman** et al, 1985). Less **effort** has been devoted to studies of **oil** effects on **zooplankton** communities in controlled marine ecosystems ~~or at~~ sites of accidental marine spills. Reviews of these studies can be found in Thomson et al. (1981), **Wells** (1982), Teal and **Howarth** (1984) and Rice et al. (1985), among others.

**Direct** effects of **oil** on **zooplankton** can include mortality and a number of sublethal responses, including reduced feeding and reduced reproductive success. Some sublethal effects may impair the fitness **of** individual **zooplankters** to the extent that their susceptibility to predation is increased. Indirect effects of **oil** on **zooplankton** may **also** occur **if oil** causes changes in the **phytoplankton** communities on which herbivorous **zooplankters** feed.

In single-species *tests*, lethal effects ~~are~~ generally encountered at oil concentrations of **0.1-10** parts per million (**ppm**), whereas sublethal effects may occur during lengthy exposures to lower oil concentrations (**Wells** 1982). For the euphausiid **Thysanoessa raschi**, 50% **mortality** occurred "after a 3 d exposure to about 2 ppm **oil** (**Fishman** et al. 1985). In uncontrolled **field** situations, behavior, habitat preference, and oceanographic processes may **alter** the likelihood of any contact between **zooplankton** and **oil**, or may **alter** exposure concentrations or times.

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\* Prepared by William E. Cross, **LGL** Ltd.

The behavior of oil in the sea is important in determining its effects on marine life. There are few published data on concentrations of oil in the water column after spills or blowouts. Concentrations under slicks are generally in the parts per billion (ppb) range (Gundlach et al. 1983). Higher concentrations, up to 50 ppm or more, have been reported near subsea blowouts or under slicks treated with dispersants. However, such high concentrations persist for very short times (minutes or hours), or are found only in very shallow water (<5 m) or near the oil source.

Pycnoclines tend to confine oil to the upper layers because there is little exchange between the water masses above and below a pycnocline. Storms and high winds, such as those that occurred in the study area in 1985 and 1986, increase the mechanical dispersion of oil and break down the pycnocline. Storms also spread the slick over a large area and thus increase evaporation of the more volatile oil fractions.

Zooplankton probably would be susceptible to oil effects only in near-surface waters and in shallow areas where restricted water circulation maintains relatively high concentrations of oil. In the cases of blowouts or use of chemical dispersants, high concentrations can occur below the water surface, but high concentrations are likely to be temporary or localized.

In the Alaskan Beaufort Sea, important zooplankton concentrations likely would encounter harmful oil concentrations only in nearshore waters. Bowheads often feed in nearshore waters. In these areas mixing caused by wave action and/or dispersants could cause the entire water column to be contaminated.

Offshore, the main concentrations of zooplankton and oil likely would remain separated by the pycnocline, which was present several meters below the surface (see 'Water Masses' section). Zooplankton biomass in the top several meters of the water column was very low in 1985-86. Studies of several major oil spills under varying oceanographic conditions have reported some oil effects on individual zooplankters (e.g. adherence or ingestion of oil, mortality), but there has been little evidence of prolonged change in open ocean zooplankton communities (Wells 1982).

Ocean currents would cause zooplankton communities in our study area to be highly transient. Only in the case of a prolonged subsea blowout within (or up-current from) a feeding area might the effects of oil on zooplankton persist for a prolonged period. Once the blowout ended, there would be rapid replenishment of the zooplankton community. Because repopulation and natural patchiness, changes in zooplankton biomass detrimental to bowhead feeding would be unlikely even from a major oil spill (MMS 1984).

The above discussion is based on possible effects of oil on zooplankton. The potential direct effects of the oil on whales are probably of more concern (see Geraci and St. Aubin 1985; Hansen 1985 for reviews). Furthermore, clean-up activities after a major oil spill would probably involve intensive boat and helicopter traffic. Vessel traffic in a feeding area will disperse bowheads at least temporarily (see next subsection). This would reduce their ability to utilize zooplankton in one specific feeding area, perhaps for the remainder of that feeding season. On the other hand, displacement by clean-up

**activities** would have the advantage of preventing further direct exposure of whales to **oil**.

In conclusion, oil spills might have a significant effect on **zooplankton** and bowhead feeding in nearshore waters in the study area, but not in offshore waters. The nearshore area harbors above-average **zooplankton** concentrations, and these are sometimes consumed by bowhead whales. The restricted circulation in nearshore zones could lead to longer exposure of **zooplankton** (or **bowheads**) to oil contamination than would be **likely** offshore. Thus, an oil **spill** affecting the nearshore zone would be of particular concern. Other than the nearshore area, no one part of the study **area** has been identified as supporting a consistently high concentration of **zooplankton** or of **feeding bowhead** whales.

#### Disturbance Effects in Bowhead Feeding Areas

Bowheads generally move away when levels of industrial noise increase rapidly to high intensities (**Ljungblad et al. 1985b**; Richardson et al. **1985b,c, 1986a**). This happens when any boat heads more or less directly toward bowheads, or when a seismic vessel approaches within a few kilometers. Avoidance also occurs when drilling or dredge **noise** begins at a **level equaling** that within a few kilometers of an actual **drillship** or dredge. Based on these results from previous studies, we would expect that the presence of these types of disturbance within a few kilometers of a feeding area would **result** in **temporary** displacement of bowheads. Results from the present study were consistent **with** expectation.

Boat Disturbance.--On three successive dates in **early** September 1986 (5-7 **Sept**), we used a 13-m diesel-powered boat to sample the concentrated **zooplankton** within a whale **feeding** area off the **Kongakut** Delta. On the 5th, the activities of the boat caused **most** if not **all** bowheads to swim rapidly offshore from the feeding area, into deeper water where **zooplankton** was much less abundant. These **whales travelled** several kilometers away from their feeding area. Whales had returned to the same feeding area by the 6th, including **three** individually recognizable animals that had been present on the 5th (**Table 41, p. 322**). By the 7th, feeding **whales** were concentrated a few kilometers farther east, including three more individuals **that** had been present on the 5th. Thereafter, few feeding **bowheads** were seen off the **Kongakut** Delta (**Fig. 127, p. 290**). These results confirm **that** temporary boat disturbance does cause displacement of bowheads from a feeding area, and that at **least** some of the displaced **whales** return to the same feeding location within 1 d. We do not know whether the **later** departure of whales from the area was attributable to the repeated boat disturbance on subsequent dates, or to some natural factor like a decrease in food abundance.

Seismic Exploration.--Noise pulses from distant seismic exploration do not cause bowhead whales to cease feeding or to **leave** feeding areas. Several of the **bowhead** concentrations that we observed in September 1985-86 were exposed to faint or moderate-intensity noise pulses from distant seismic operations (p. 338-341; Richardson et al. **1986b, p. 200**). Despite this, most of these whales were feeding. Some recognizable individual bowheads remained in the **Komakuk** area for at **least** several days in September 1985 despite the fact that this area was repeatedly ensonified by faint-moderate seismic

pulses. Seismic vessels were not visible from our aircraft during behavioral observations, which indicates that the ships must have been >10 km away, and in most cases >20 km away.

These results were consistent with those of previous studies, which have shown that bowheads continue their normal activities when exposed to noise pulses from seismic vessels more than a few kilometers away (Reeves et al. 1984; **Ljungblad** et al. 1985b; Richardson et al. 1985b,c, 1986a). There are indications that seismic noise pulses may sometimes cause subtle changes in surfacing, respiration and diving behavior at distances considerably greater than the several kilometer radius within which definite changes in behavior are evident (Richardson et al. 1986a). However, our 1985-86 results from the Eastern Alaskan Beaufort Sea provided no clear evidence of these types of distant effects.

When seismic vessels approach within a few kilometers of bowheads, the feeding or other activities of the whales are disrupted and the whales are displaced (**Ljungblad** et al. 1985b; Richardson et al. 1985c, 1986a). Seismic vessels are inherently mobile, so a given feeding location is unlikely to be exposed continuously to strong seismic impulses. More commonly, whales feeding in one location are exposed much of the time to 'faint' noise pulses from a distant seismic vessel, with occasional periods of more intense noise when the ship is close. Concentrations of feeding **bowheads** have been observed to remain in various areas under these conditions. For example, bowheads remained in part of Mackenzie Bay for several weeks during August 1984 despite occasional passes through the area by a high-energy seismic vessel (Richardson et al. 1985a). One day after the operating seismic ship passed within 1½ km of feeding bowheads, bowheads were seen at the same approximate **location** (Richardson et al. 1985c, 1986a). We do not know whether some of the same individual whales were present during repeated approaches by the seismic vessel, but bowheads as a group continued to feed in the area of **ongoing** seismic exploration.

The above observations refer primarily to high-energy seismic vessels that normally travel along lines tens of kilometers long before doubling back toward the same **area**. In contrast, operations of high-resolution seismic vessels typically are concentrated within an **area only** a few kilometers wide. If such an area coincided with a bowhead feeding area, whales might be subjected to such frequent disturbance by either the noise pulses or the seismic vessel itself that displacement might occur.

Stationary Industrial Sites.--Offshore construction **sites** and **drillships** (**plus** associated support vessels) introduce considerable noise into the sea. These industrial activities, unlike shipping and most high-energy seismic programs, often continue at a specific site for prolonged periods.

Some bowheads feed in areas **enisonified** by **drillships** and dredges (Richardson et al. 1985b,c). For example, during early August 1980 feeding bowheads were present near an island construction operation north of the Mackenzie Delta. Many whales were well within the zone **enisonified** by underwater noise from the dredge and associated vessels, occasionally <1 km away (Richardson et al. 1985b,c). Similarly, bowheads were seen as close-as 4 km from **drillships**, again well within the **enisonified** zone.

The **observations** quoted above do not demonstrate that the activities of **bowheads** are unaffected by ongoing **noise** from **drillships** or dredges a few kilometers away. There is no information about the numbers of whales that would have been present in the absence of the industrial activities. Based on other types of information, we believe that the presence of a stationary industrial site will reduce the utilization of the surrounding area by bowheads, probably to a **radius** exceeding the 'closest point of approach' distances mentioned above. For example, playback experiments show that feeding **bowheads** are sometimes displaced when exposed to **drillship** or dredge noise at **levels** equaling those several kilometers from the actual industrial activity (Richardson et al. 1985c). Although the playback experiments did not fully duplicate noise conditions near an actual **drillship** or dredge, the responses of the whales were not startle reactions in the usual sense; the industrial noise **levels** during playbacks were increased gradually over 10 rein, not suddenly.

A further consideration is that offshore industrial sites usually involve some vessel traffic. **Drillships**, for example, are invariably attended by support vessels. Vessel traffic within 1-4 km is known to disturb bowhead whales, and some of the documented cases have involved the types of supply ships used to support offshore drilling (Richardson et al. 1985b,c). A moving support vessel may be more disturbing to whales than is the noise from a stationary **drillship** or dredge per se.

These considerations suggest that the presence of a **drillship** or dredge in a feeding area would reduce the utilization of that area by bowhead whales. The radius of the affected area is difficult to predict, but could be several kilometers based on the playback and boat disturbance results (see also Miles et al. 1986, in prep.).

Significance of Disturbance to Feeding Whales. --Temporary interruption of feeding by a single passing ship or seismic exploration vessel probably would not have a significant effect on the energy balance of a whale. Single disturbance incidents do not appear to cause permanent displacement from a feeding area, and probably interrupt **feeding** for no more than a few hours. However, if there were repeated incidents of vessel or seismic disturbance, the whales might be displaced from that feeding area for the remainder of the feeding season. This might occur in a feeding area just offshore from a heavily-used port, or in an area where a high-resolution seismic vessel was concentrating its activities. Intensive vessel activities associated with clean-up of an oil spill could also displace bowheads.

In our study area, nearshore feeding areas extended offshore for only a few kilometers or less. The onshore-offshore dimensions of these feeding areas were similar to the distances at which utilization by bowheads could be affected by ongoing industrial activities. The alongshore dimensions of these feeding areas are unknown but probably greater (Mackas et al. 1985), perhaps extending intermittently from our study area to the Mackenzie Delta. A stationary industrial site probably would reduce utilization of a nearshore feeding area only if the zooplankton 'patch' were (1) localized in the alongshore as well as the onshore-offshore direction, and (2) relatively static in position over time.

In offshore waters of the Eastern Alaskan Beaufort Sea, there is no evidence that either feeding bowheads or dense zooplankton patches recur regularly at specific sites. Feeding locations in offshore waters seem quite variable and transitory within and between years (e.g. Fig. 109 on p. 260 and this study). The permanence of zooplankton patches in offshore waters of our study area has not been studied. However, patch locations are expected to change with the movements of water masses, whose positions vary in response to wind and other factors. Thus, even if bowheads are excluded from an area around a stationary industrial site in offshore waters, that site probably would have been a suitable feeding area only intermittently.

In some nearshore areas, feeding bowheads occur for prolonged periods, e.g. in southern Mackenzie Bay and off Komakuk. Within the official study area, nearshore feeding occurred off the Kongakut Delta for a few days in 1986. Ongoing industrial activities in those types of areas might cause site-specific reductions in utilization by feeding whales. Marine construction or presence of a port might be the activities of most concern in these nearshore areas, (Drillships are unlikely to be used in shallow water, and drilling on artificial islands does not introduce high noise levels into the water--Greene, in Johnson et al. 1986; Miles et al. 1986.) Feeding whales are often distributed along 10-50 km of coast in these nearshore areas. Disturbance effects from one industrial site might extend several kilometers in either direction along the coast, but not for 25 km. Thus, a single nearshore industrial site might displace bowheads from all parts of a small nearshore feeding area, but probably not from an elongated one. A greater concern would be the effect of multiple activities distributed along a significant length of coast. That situation might deny bowheads the use of an entire nearshore feeding area.

We conclude that noise from a marine construction site or drillsite could exclude bowheads from an area with a radius of a few kilometers.. This area could include a significant fraction of a patch of concentrated zooplankton. Offshore, suitable feeding locations are apparently not at fixed positions and no one site is likely to remain a potential feeding area for long. Thus exclusion of whales from an offshore site is not likely to result in prolonged exclusion from an important feeding area. Certain nearshore areas do seem to be recurring feeding areas. Presence of ongoing industrial activity in one of these recurring nearshore feeding areas is a greater concern. Construction activities and drilling typically occur at a given location for several weeks, which could span the entire period when bowheads might feed in an area.

What is the significance of exclusion from a feeding area? At any one time, a minority of the Eastern Alaskan study area contained, at some depth, a biomass of zooplankton sufficiently high to support efficient feeding by bowheads--about 16% of the continental shelf portion of the study area in 1985 and 5% in 1986 according to our estimates (p. 456). Although these percentages are low, they represent a large total area with sufficient food for efficient feeding. Also, patches are transitory and over a period of time a larger proportion of the study area would contain at some depth a biomass of zooplankton sufficiently high to support efficient feeding. Bowheads were absent from most of the potential feeding sites along the broad-scale transects. It is not known whether all of these apparent prey patches actually contained prey suitable for bowheads, or how difficult it would be for

bowheads to find these patches. However, the **hydroacoustic** data suggested that, within the study area, there are at **any** one time in **late** summer many unexploited locations with sufficient **zooplankton** to make feeding energetically worthwhile. If so, displacement of bowheads from one or a few feeding locations probably would not prevent them from feeding elsewhere within the study area.

The above argument pertains to the continental shelf region as a **whole**, as sampled by the broad-scale transects. The shallow nearshore zone, which is **a** Preferred feeding area for **subadult** bowheads in **late** summer of some **years**, **includes** only a small proportion of the study area, and an even smaller proportion **of** the water volume. A higher proportion of the nearshore **zooplankton** patches than of the total **patches** in the study area may **be** exploited by bowheads. However, patches of unexploited **zooplankton** were found along the nearshore portions of some broad-scale transects (Fig. 99-100, p. 220-222). This suggests that even in nearshore waters of the Eastern Alaskan Beaufort **Sea**, **whales** displaced from one feeding site **could** find previously unexploited alternate feeding sites elsewhere along the coast, **It** is uncertain whether this would also be true farther east, along the Yukon coast, where utilization of nearshore waters by **subadult** bowheads is, in some years, more intensive and consistent.

A large proportion of the patches found along the broad-scale transects in early-mid September may be used by migrating bowheads during the peak of migration in late September. Many of the bowheads **that** we observed in the middle shelf region in **late** September **of** 1985-86 were feeding as they **travelled** west. "Almost **all** bowheads taken at **Kaktovik** in autumn contain fresh **zooplankton** in their stomachs (Lowry and Frost 1984; Lowry et al. 1987). Given that the bowhead population travels west over **all** parts of the nearshore, inner shelf, middle shelf and outer **shelf** region, each **zooplankton** concentration present in these areas might be used at **least briefly** by some migrating whales.





## CONCLUSIONS\*

Most members of the Western Arctic population of **bowhead** whales migrate through the Alaskan Beaufort Sea during September and October while en route from the main summer feeding grounds in the Canadian Beaufort Sea to the wintering grounds in the Bering Sea. Some feeding occurs within the Alaskan **Beaufort** Sea during **late** summer and **early** autumn. It has been hypothesized that this late summer feeding may be especially important to **bowheads** because they may not feed again for several months after leaving the **Beaufort** Sea, and because the energy content of arctic **zooplankton** is high. in **late** summer.

To evaluate the possible effects of offshore **oil** exploration in the Eastern Alaskan **Beaufort** Sea on bowhead whales, it was necessary to evaluate the importance of the area to feeding **bowheads**. The general purpose of the two-year project was to quantify what proportion of the annual energy requirements of the Western Arctic bowhead **whale** stock is provided by food resources located in the Eastern Alaskan Beaufort Sea (Alaska/Canada border to **144°W**). Specific objectives were to

1. Determine the concentration and distribution of the **planktonic** food of bowhead whales in the Eastern Alaskan Beaufort Sea and correlate with known oceanographic features.
2. Estimate the number of bowhead **whales** utilizing the Eastern Alaskan **Beaufort** Sea as a feeding area during the summer and **fall**; observe and document their feeding **activities**, behavior and residence times.
3. Estimate the degree of utilization of available food resources in the Eastern Alaskan Beaufort Sea by the Western Arctic bowhead whale stock; evaluate the **null** hypothesis that food resources consumed there do not contribute significantly to the **annual** energy requirements of the stock.

This section states the overall conclusions relating to these three objectives. More specific conclusions pertaining to each section of the **report** can be found in the **Executive** Summary at the **front** of this volume, or at the **end** of each disciplinary chapter.

### Utilization of Study Area by Bowhead Whales

In some years, **like** 1986, the western edge of the main summer feeding range extends into the Eastern Alaskan Beaufort Sea before the start of active westward migration. **In other years**, like 1985, very few whales occur in the study area until the main period of westward migration from Canadian waters begins in mid September. **Small** numbers of bowheads often **occur** in the **study** area during parts of August, usually **well** offshore. They are **suspected** to feed, but this has not been observed directly.

Many feeding bowheads linger along the **Yukon** coast just east of the official study area during late summer of some **years**, including 1985-86. Several recognizable **whales** were re-photographed **there** on **later** days and/or

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\* By W. John Richardson and **Denis H.** Thomson, LGL Ltd.

the next year. Within **years**, minimum residence times averaged 7.6 d ( $n = 11$ ), with a maximum documented period of 16 d. In 1986, this nearshore **concentration** extended west into the southeast part of the Eastern Alaskan study area for a few days in early September. Most bowheads feeding in these nearshore areas were **subadults** 7-13 m long.

The main period of westward migration through the Eastern Alaskan Beaufort Sea is from mid September to early -October, with some variation between years. Whales tend to be closer to shore in September and October than in August; most travel west over the continental shelf. In 1985-86, whales **migrating** west over the middle part of the shelf during late September included many adults (some with calves) as **well** as large **subadults**.

Many if not all bowheads migrating west over the shelf during September feed intermittently while traveling, based on behavioral observations and stomach content data from the **Kaktovik** hunt. Whales in the middle-shelf area in late September of 1985-86 did not seem to linger in any **one** area for long; there were no between-day reidentification at middle-shelf feeding sites. When feeding whales were **observed** at middle-shelf sites, their headings when they surfaced to breathe **sometimes** were predominantly westward, suggesting that they were migrating gradually westward as they fed.

Feeding behavior within the study area was similar to that on the main summering grounds in Canadian waters. Most feeding in both nearshore and deeper waters was well below the surface, consistent with the observed low **abundance** of **zooplankton** in surface waters. Feeding continued when whales were exposed to faint-moderate intensity noise pulses from distant seismic vessels. Observed feeding locations in the Eastern Alaskan Beaufort Sea differed between years. No one **site** has been identified as a consistent feeding location.

Even after allowance for the many whales present but undetectable during aerial surveys, numbers in the study area in 1985 were very low (estimated as <100) at all times during late summer and **early** autumn. About 220-370 **were** present at various times in September 1986. Utilization of the study **area** in August-October was estimated as about 4200 whale-days in 1985 and 13,000 whale-days in 1986. The 1985 value may be an underestimate, given that it is barely adequate to account for steady westward migration of a population of 4417 whales across the study area, and inadequate if the population size is about 7200 as is now suspected. In any case, utilization of the study area for feeding was less than average in **1985**. Utilization was greater in **1986** than in 1985, but apparently not as high as in some other years.

### **Zooplankton and Oceanographic Features**

The composition of the **zooplankton** in the Eastern Alaskan Beaufort Sea was similar to that elsewhere along the Beaufort Sea coast and in other arctic regions. Copepods were the dominant organisms. The small **copepod** **Limnocalanus macrurus** dominated in shallow nearshore waters; the large **copepods** **Calanus hyperboreus** and **C. glacialis** dominated farther offshore. In both years, **euphausiids** and **mysids** were *most* abundant near the bottom in nearshore waters. Whether they **also** occurred in similar abundances near the bottom farther offshore is unknown. In October 1986, **euphausiids** were more abundant farther

west, between Pt. Barrow and Prudhoe Bay, than in the Eastern Alaskan study area.

In September 1985-86, average **zooplankton** biomass was highest in the nearshore and inner shelf areas (south of the 50 m contour), and lower on the **outer shelf** (north of the 50 m contour). Mean **biomasses** in the top 50 m of water over the **continental** shelf and slope were much higher than previously reported for the Arctic Ocean farther offshore. Average **zooplankton** biomass (wet weight) in the top 50 m within our study area was about  $0.2 \text{ g/m}^3$ , similar to **biomasses** on the main summering grounds of bowheads in the Canadian Beaufort Sea.

Hydroacoustic surveys showed that **zooplankton distribution** was patchy. **Zooplankton patches** often extended for several kilometers in the horizontal plane, but usually were only a few meters thick.

Dense **zooplankton** patches containing mainly **Limnocalanus macrurus** were found at nearshore locations where bowheads fed. The biomass (wet weight) averaged about  $2 \text{ g/m}^3$  at the depth of maximum biomass. **Zooplankton** biomass at whale feeding stations in the study area was higher than at control stations, but similar to biomass at nearshore feeding locations in the Canadian Beaufort Sea. Although major efforts were made to minimize the various biases normally associated with **zooplankton** sampling, this  $2 \text{ g/m}^3$  figure is probably an underestimate of the mean biomass in the water filtered by bowheads.

Dense layers of concentrated zooplankton were most common in nearshore waters, especially near feeding bowheads, but also occurred farther offshore over the continental shelf. **Calanus** usually dominated in these offshore patches. Although the offshore patches were not being used by feeding bowheads during our **zooplankton** sampling periods in early-mid September, they probably were used by migrating bowheads in late September.

We had only limited success in accounting for the patchy distribution of **zooplankton**, and thus the feeding locations of bowheads, on the basis of water mass characteristics. **Zooplankton** was concentrated in a subsurface mass of cold saline water present in parts of the nearshore zone in 1986; these were the areas where whales were feeding. **Zooplankton** often concentrated near the strong pycnocline present several meters below the surface in 1985. **Zooplankton** biomass in surface waters above the pycnocline was low, and biomass near surface fronts was, at most, only slightly elevated. There was only a general association of elevated biomass with an area of upwelling in inner shelf waters in 1985, and no clear evidence of concentrated **zooplankton** in or near an intrusion of Bering Sea Water present near the shelf break in 1986. A better understanding of the biology of **L. macrurus** in arctic nearshore areas is needed in order to understand the importance of coastal waters to the subadult bowheads that concentrate there in some years.

Copepods had a higher energy content per unit weight than other major groups, and accounted for about 90% of the total caloric content of the **zooplankton**. Mean caloric content of the **zooplankton**, on a 'per cubic meter' basis, was about  $200 \text{ cal/m}^3$  in the top 50 m of the water column over the continental shelf as a whole, but  $2132 \text{ cal/m}^3$  in the dense layers of copepods at whale feeding sites.

### Energetic Importance of Study Area to Bowheads

Bowheads must feed in areas where the biomass of zooplankton exceeds the average biomass in the Beaufort Sea, which is about  $0.2 \text{ g/m}^3$ . Theoretical calculations indicate that an average bowhead must feed at locations where average **zooplankton** biomass is at least  $2\frac{1}{2} \text{ g/m}^3$  if it is to acquire its annual food requirement in 130 d feeding for 16 h/d. The average prey biomass at summer feeding locations would need to be  $2 \text{ g/m}^3$  if 30% of daily maintenance requirements were met by supplementary feeding during the rest of **the** year. These theoretical figures are generally consistent with the observed mean zooplankton biomass at **bowhead** feeding sites ( $2 \text{ g/m}^3$  at depth of maximum biomass), especially if allowance is made for the fact that the observed values are probably underestimates of the food consumed by whales.

The annual food requirement for a population of 4417 bowheads is estimated to be 421,000 MT (metric tons), with broad confidence limits. This value is higher than some previous estimates, primarily because the caloric content of **zooplankton** in the Beaufort Sea, on a wet weight basis, is lower than assumed **in** some previous analyses. Numerous other refinements in the estimation process have also been made. If the population size is about 7200 **whales** as is now suspected, their annual food requirement would be about 690,000 MT.

The **total** amount of zooplankton in the top 50 m of the water column within the Eastern Alaskan study area was estimated as about 150,000 MT **in** late summer. Of this, about **75,000** MT was over the continental shelf where most bowhead feeding occurs. Thus, zooplankton in the study area represented a significant percentage of the **annual** population requirement of about 421,000 MT for 4417 bowheads. However, of the 75,000 MT over the continental **shelf**, only about 8100 MT (**1985**) or 1100 MT (1986) was, at any one **time**, **in** concentrations sufficiently dense to permit economical **feeding** by bowheads. These **amounts are very** small percentages of the annual population **requirement**.

The estimated whale-days of utilization figures for 1985 (4200 whale-d) and 1986 (13,000 whale-d) **also** indicate that the Western Arctic bowhead **population** acquired very little of its annual food requirement in the study area in those **years**. If these bowheads fed in water with an average of  $2 \text{ g/m}^3$  of **zooplankton** for 12 h/d at a swimming speed of 5 km/h, they would have consumed only about 2000 MT in 1985 and 6060 MT in 1986. This consumption represents only 0.5% and **1.4%**, respectively, of the estimated annual food requirement of 4417 bowheads (421,000 MT). These estimates are approximate, but the percentages **would** remain low even if prey consumption were several times higher due to errors in the assumptions or to more intensive utilization of the study area in certain years. The percentages would be even lower if population size is about 7200 with an annual prey requirement of about 690,000 MT\*

In some years, like 1986, a small number of bowheads feed in the study area for at least several **days**—longer than the "population average. If a **subadult** bowhead spent 10 days—feeding for 16 h/d in water with  $2 \text{ g/m}^3$  of zooplankton, it would consume about 6-8% of its estimated annual food requirement. Some whales probably find prey concentrations exceeding  $2 \text{ g/m}^3$ , and it is possible (although unproven) that a few whales may feed in the study

area for more than 10 d in some *years*. If so, those **few** individuals **could** obtain **an** appreciable fraction of their "annual food in the study **area**.

The **relative** amounts of feeding in the Canadian vs. Eastern Alaskan **Beaufort** Sea are not known precisely, but Canadian waters clearly are much more important. Most Western Arctic **bowheads** are in **the** Canadian **Beaufort** Sea for at **least**  $3\frac{1}{2}$ -4 mo. In contrast, an average **bowhead** apparently feeds for no more than a few days in the "Eastern Alaskan Beaufort Sea (estimated as roughly 1-2 d in 1985 and 3-4 d **in** 1986).

Some feeding **by** bowheads occurs in late autumn, **winter** and spring west of **our** study area. **Carbon isotope** ratios in **zooplankton** and bowhead tissues suggest that this feeding may be more extensive than formerly **thought**, at **least in subadult bowheads**. Present uncertainty **about** the amount of feeding in these seasons is an important limitation in understanding food requirements in the Beaufort Sea as a whole. However, it has **little** effect on conclusions about the importance of the Eastern Alaskan Beaufort Sea.

For the population as a whole, the results indicate that the **null** hypothesis **can** be accepted:

Food resources consumed in the Eastern Alaskan Beaufort Sea do not contribute significantly to the **annual** energy needs of **the** Western Arctic **bowhead** stock.

**An** analogous conclusion can be drawn for most individual bowheads in most years. However, in some years a few animals that feed in the study area for **longer** than others may acquire a significant fraction of their annual energy needs in the study area.



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Table 71. Biomass(mg/m<sup>3</sup>) of each major zooplankton group collected in oblique and surface horizontal tows in the study area during September 1986.

Tran. No.	Sta. No.	Samp. No.	Tow Type	Depth (m)	Depth (m)	Water Mess	Copepods mg/m <sup>3</sup>	Pteropods mg/m <sup>3</sup>	Mysids mg/m <sup>3</sup>	Euphausiids mg/m <sup>3</sup>	Amphipods mg/m <sup>3</sup>	Larvae mg/m <sup>3</sup>	Hydrozoans+ Ctenophores mg/m <sup>3</sup>	Ctenophores mg/m <sup>3</sup>	Decapod Larvae mg/m <sup>3</sup>	Other Taxa mg/m <sup>3</sup>	Total-Detritus mg/m <sup>3</sup>
1	1	120	0	9	10	1	70.86	0.73	0.05	0.00	1.37	1.14	2.41	0.21	0.38	1.27	78.41
1	2	124	0	30	34	1	144.16	0.19	0.00	4.85	2.63	12.87	45.54	2.16	9.74	0.82	222.95
2	1	142	0	8	10	1	46.00	0.11	0.00	0.00	4.53	3.54	0.69	0.11	0.00	0.55	55.53
2	2	146	0	22	26	1	717.89	6.72	0.95	0.13	10.90	9.26	8.13	5.94	13.08	3.86	776.85
3	1	79	0	9	13	1	12.88	2.99	0.00	0.00	2.09	2.77	21.04	0.03	6.99	1.47	50.27
3	2	83	0	18	21	1	2.81	7.47	0.76	0.90	7.15	17.42	14.25	0.07	93.23	2.81	146.86
4	1	57	0	10	12	1	1001.20	0.66	4.80	0.00	0.32	14.53	3.35	0.50	0.45	0.00	035.81
4	2	62	0	18	21	1	0.47	0.05	0.00	0.00	0.51	0.00	0.16	0.98	1.68	0.12	3.99
1	3	129	0	40	47	2	236.49	4.66	1.50	0.89	20.59	2.65	23.33	20.51	2.26	4.18	317.06
3	3	87	0	35	41	2	48.59	2.61	0.00	1.98	22.35	15.77	12.95	0.99	3.23	4.18	112.65
4	3	66	0	40	43	2	6.92	18.37	0.00	0.78	5.82	18.21	28.10	0.88	1.44	0.73	81.24
1	4	133	0	50	54	3	4.93	2.26	0.00	0.00	6.01	2.20	4.76	1.02	0.33	3.22	24.73
1	5	138	0	50	118	3	0.72	0.18	0.00	0.00	3.76	3.02	48.98	0.54	0.02	0.19	57.41
2	5	150	0	so	150	3	1.24	0.03	0.00	0.00	7.92	0.00	21.78	2.36	0.00	10.59	43.92
2	5	151	0	100	150	3	11.68	0.05	0.00	0.00	3.81	18.73	23.55	8.27	0.00	0.20	66.29
3	4	91	0	50	53	3	33.04	2.88	0.00	0.00	10.43	9.69	6.63	2.89	0.00	2.55	68.11
3	5	95	0	50	205	3	1.36	1.34	0.00	0.00	4.27	1.42	4.38	0.15	0.30	4.96	18.19
4	4	71	0	50	53	3	0.41	2.73	0.00	0.00	5.54	1.94	9.70	0.19	0.36	0.38	21.26
4	5	75	0	50	180	3	18.70	1.42	0.00	0.01	1.38	0.51	13.95	28.50	0.00	0.66	65.13
WF	1	2	0	16	17	1	13.97	5.00	5.66	0.17	12.54	2.77	36.74	2.93	13.37	3.20	96.36
WF	5	19	0	12	14	1	1179.07	0.58	2.09	0.31	1.85	7.58	30.59	2.73	3.35	0.00	1228.16
WF	7	27	0	8	11	1	777.10	0.09	53.38	0.15	4.04	0.51	6.72	0.22	0.55	10.61	853.38
WF	9	36	0	5	7	1	165.83	0.24	127.43	0.00	6.26	4.87	13.49	0.13	0.00	0.28	318.54
WF	10	39	0	9	12	1	35.44	3.01	4.85	0.00	2.01	7.91	43.81	0.12	6.33	1.53	105.01
WF	12	48	0	18	22	1	869.90	1.04	2.17	0.00	5.80	11.02	10.61	6.94	0.71	4.21	912.39
CTL	11	44	0	12	15	1	114.01	0.48	0.38	1.84	3.82	6.39	53.23	6.80	7.74	3.83	198.53
CTL	2	7	0	20	25	1	40.68	0.26	0.00	0.00	0.61	3.04	2.89	0.73	2.49	1.10	51.79
CTL	6	23	0	22	27	2	14.05	11.36	0.00	0.00	3.24	12.74	30.94	1.02	5.86	2.00	81.19

ZOOPLANKTON BIOMASSES FROM CONVENTIONAL BONGO TOWS, 1986

# APPENDIX I

Table 71 (Concluded).

Tran. No.	Sta. No.	Samp. No.	Tow <sup>1</sup> Type	Tow Depth (m)	Sta. Depth (m)	Water <sup>2</sup> Mass	Copepods mg/m <sup>3</sup>	Pteropods mg/m <sup>3</sup>	Mysids mg/m <sup>3</sup>	Euphausiids mg/m <sup>3</sup>	Amphipods mg/m <sup>3</sup>	Fish Larvae mg/m <sup>3</sup>	Hydrozoans+ Ctenophores mg/m <sup>3</sup>	Chaetognaths mg/m <sup>3</sup>	Decapod Larvae mg/m <sup>3</sup>	Other Taxa mg/m <sup>3</sup>	Total-Detritus mg/m <sup>3</sup>
CTL	8	32	O	18	23	2	12.83	0.96	0.00	0.00	15.39	0.00	4.96	1.33	1.72	3.32	40.51
CTL	13	53	O	21	25	2	0.65	5.76	0.00	0.00	0.69	19.79	9.74	0.03	14.54	7.47	58.67
1	1	119	H	O	10	1	49.41	0.04	0.00	0.00	2.54	0.00	2.17	0.1	10.39	1.69	56.35
3	1	78	H	O	13	1	1.10	0.28	0.00	0.00	0.59	0.00	2.02	0.24	0.00	0.72	4.96
4	1	56	H	O	12	1	144.04	0.55	0.42	0.00	0.14	0.66	3.30	0.00	0.00	0.19	149.30
1	3	128	H	O	47	2	1.02	0.01	0.00	0.00	0.03	0.09	0.13	0.13	0.01	0.05	1.48
3	3	86	H	O	41	2	0.55	0.07	0.00	0.00	0.01	0.93	0.42	0.01	0.09	0.07	2.14
4	3	65	H	O	43	2	1.24	0.57	0.00	0.00	2.48	1.47	13.53	1.74	14.07	0.01	35.42
1	5	137	H	O	118	3	0.37	0.03	0.00	0.00	0.09	0.80	0.82	0.05	0.07	0.27	1.01
2	5	149	H	O	150	3	0.60	0.01	0.00	0.00	0.27	4.89	0.19	0.01	0.00	0.05	6.01
3	5	94	H	O	205	3	0.04	0.01	0.00	0.00	0.14	0.00	0.00	0.0	10.01	0.04	0.24
4	5	74	H	O	180	3	0.09	0.00	0.00	0.00	0.29	0.11	0.07	0.01	0.07	0.40	1.03
WF	1	1	H	O	17	1	0.05	0.24	0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.00	0.67
WF	5	18	H	O	14	1	0.47	1.94	0.00	0.00	0.58	0.00	0.84	0.00	0.02	0.30	3.84
WF	7	26	H	O	11	1	7.62	0.08	0.00	0.00	1.93	0.26	9.06	0.02	0.00	0.09	19.06
WF	9	35	H	O	7	1	67.39	0.00	0.15	0.00	1.29	0.22	4.99	0.10	0.00	0.10	74.24
WF	10	38	H	O	12	1	8.36	1.09	0.13	0.00	0.09	0.94	3.88	0.03	3.86	0.57	18.95
WF	12	47	H	O	22	1	2.37	0.03	0.00	0.00	0.02	0.07	1.26	0.01	0.00	0.14	3.90
CTL	11	43	H	O	15	1	0.41	1.76	0.00	0.00	0.05	4.57	13.72	0.00	9.42	0.17	30.11
CTL	2	6	H	O	25	1	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.10	0.29
CTL	6	22	H	O	27	2	0.21	6.35	0.00	0.00	0.28	0.00	1.72	0.00	0.12	0.02	8.70
CTL	8	31	H	O	23	2	0.47	0.00	0.01	0.00	0.04	0.00	1.37	0.00	0.00	0.01	1.90
CTL	13	52	H	O	25	2	4.33	0.06	0.00	0.00	0.00	0.00	0.03	0.00	0.01	0.11	4.54

<sup>1</sup> Tow Type: O = Oblique, H = Surface horizontal.<sup>2</sup> Water Masses: 1 = Nearshore, 2 = Inner Shelf, 3 = Outer Shelf.

Table 72. Biomass (mg/m<sup>3</sup>) of dominant zooplankton species collected in selected surface horizontal, oblique and vertical tows in the study area, September and October 1986.

Tran. No.	Sta. No.	Samp. No.	Tow Type	Depth (m)	Water Mass	Copepods						Total Copepods mg/m <sup>3</sup>	Hydrozoans and Ctenophores				Pteropods
						Calanus Hyperboreus	Calanus glacialis	Pseudocalanus minutus	Euchaeta glacialis	Metricia longa	Limnocalanus macrurus		Halitholus cirratus	Aglantha digitale	Staurophora mertensii	Mertensia ovum	Spiratella helicina
						mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>		mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>
CTL	11	43	II	0	1	0.00	0.00	0.01	0.05	0.00	0.32	0.41	6.24	7.32	0.00	0.00	1.72
CTL	2	6	H	0	1	0.10	0.00	0.01	0.00	0.00	0.07	0.17	0.00	0.00	0.00	0.00	0.00
CTL	6	22	H	0	2	0.05	0.00	0.00	0.00	0.00	0.16	0.21	1.55	0.02	0.00	0.00	6.35
CTL	8	31	H	0	2	0.00	0.02	0.01	0.00	0.00	0.35	0.47	0.56	0.06	0.00	0.00	0.00
CTL	13	52	H	0	2	0.00	0.05	0.02	0.00	0.00	3.80	4.33	0.00	0.03	0.00	0.00	0.006
WF	1	1	H	0	1	0.04	0.00	0.00	0.00	0.00	0.02	0.05	0.00	0.15	0.00	0.02	0.22
WF	5	18	H	0	1	0.00	0.12	0.07	0.00	0.02	0.25	0.47	0.00	0.08	0.00	0.27	1.88
WF	7	26	H	0	1	0.46	1.00	3.98	0.00	0.05	2.07	7.62	7.16	0.49	0.00	0.00	0.06
WF	9	35	H	0	1	0.00	0.28	3.05	0.00	0.00	63.69	67.39	0.00	3.77	0.00	1.22	0.00
WF	10	38	H	0	1	0.00	0.25	0.17	0.00	0.00	7.72	8.36	0.00	2.14	0.00	1.53	1.04
WF	12	47	H	0	1	0.21	0.04	0.06	0.00	0.02	1.84	2.37	0.00	0.00	0.00	0.65	0.03
WF	12	49	H	13	1	7.33	24.36	3.23	1.77	0.00	283.04	322.97	11.40	0.78	0.00	3.82	0.13
WF	12	50	H	6	1	0.00	1.23	1.58	0.00	0.00	299.92	302.98	0.00	1.17	0.00	0.00	0.37
WF	12	51	H	15	1	5.72	11.19	3.98	0.00	0.99	018.64	1048.48	0.00	0.00	0.00	4.19	0.00
WF	1	2	O	16	1	2.19	2.45	1.30	0.25	0.10	7.37	13.97	3.53	25.17	0.00	2.11	4.97
WF	5	19	O	12	1	0.87	3.04	6.09	3.48	0.00	162.11	1179.07	22.75	0.00	0.00	6.91	0.58
WF	7	27	O	8	1	3.10	6.63	1.06	0.00	0.00	754.10	777.10	3.30	1.12	0.00	1.61	0.09
WF	9	36	O	5	1	0.54	0.54	1.80	0.00	0.00	162.59	165.83	6.48	6.24	0.00	0.00	0.24
WF	10	39	O	9	1	0.28	0.85	0.42	0.19	0.14	33.56	35.44	17.63	21.31	0.00	1.34	2.57
WF	12	48	O	18	1	1.30	5.21	4.35	1.30	1.30	855.56	869.90	0.00	4.15	0.00	4.68	1.04
CTL	2	7	O	20	1	9.20	6.07	0.77	1.21	0.99	22.25	40.68	0.00	2.43	0.00	0.15	0.26
CTL	6	23	O	22	2	1.21	8.77	0.43	0.00	0.00	3.35	14.05	8.98	15.12	0.00	3.07	11.11
CTL	8	32	O	18	2	1.07	1.87	0.36	1.43	0.53	7.49	12.83	0.00	2.81	0.00	0.00	0.96
CTL	11	44	O	12	1	4.25	13.59	2.48	0.71	0.24	92.75	114.01	0.00	50.09	0.00	0.81	0.34
CTL	13	53	O	21	2	0.00	0.02	0.02	0.00	0.00	0.58	0.65	0.00	8.47	0.00	0.79	5.64

Table 72 (Continued).

Tran. No.	Sta. No.	Samp. No.	Tow Type	Tow Depth (m)	Water Mass	Mysids		Chaetognaths		Parathemisto libellula		Boreogadus salda	Total Biomass mg/m <sup>3</sup>
						Mysids juveniles mg/m <sup>3</sup>	Mysids Mysis Itoralis mg/m <sup>3</sup>	Thysanoessa raschii mg/m <sup>3</sup>	Sagitta elegans mg/m <sup>3</sup>	Parathemisto libellula mg/m <sup>3</sup>	Boreogadus salda mg/m <sup>3</sup>		
CTL 2	6	22	H	0	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30.11
CTL 6	31	31	H	0	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29
CTL 8	52	52	H	0	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.70
CTL 13	1	1	H	0	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.90
WF 1	18	18	H	0	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.54
WF 5	26	26	H	0	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67
WF 7	35	35	H	0	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.84
WF 9	38	38	H	0	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.06
WF 10	47	47	H	0	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	74.24
WF 12	49	49	H	0	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.95
WF 12	50	50	H	13	1	0.00	0.35	0.00	0.00	0.00	0.00	0.00	3.90
WF 12	51	51	H	6	1	0.00	0.00	0.00	5.60	0.29	0.00	0.00	392.82
WF 12	51	51	H	15	1	0.00	0.00	0.00	0.69	0.00	0.00	0.00	318.95
WF 1	2	2	0	16	1	0.00	2.95	0.17	1.80	0.00	0.00	0.00	1101.54
WF 5	19	19	0	12	1	0.00	1.45	0.31	2.87	10.04	2.27	2.27	96.36
WF 7	27	27	0	8	1	49.91	3.48	0.15	2.73	0.00	2.12	2.12	228.16
WF 9	36	36	0	5	1	27.05	0.00	0.00	0.22	0.21	0.51	0.51	853.38
WF 10	39	39	0	9	1	0.00	0.00	0.00	0.13	0.47	0.00	0.00	318.54
WF 12	48	48	0	18	1	1.18	0.39	0.00	0.00	0.11	5.48	5.48	105.01
CTL 2	7	7	0	20	1	0.00	0.00	0.00	3.00	0.41	4.42	4.42	912.39
CTL 6	23	23	0	22	2	0.00	0.00	0.00	0.14	0.42	3.04	3.04	51.79
CTL 8	32	32	0	18	2	0.00	0.00	0.00	0.73	1.89	0.41	0.41	81.19
CTL 11	44	44	0	12	1	0.00	0.00	0.00	1.15	14.65	0.00	0.00	40.51
CTL 13	53	53	0	21	2	0.00	0.00	0.00	6.39	0.21	0.00	0.00	198.53
CTL 13	53	53	0	21	2	0.00	0.00	0.00	0.00	0.38	1.50	1.50	58.67

Table 72 (Continued)].

Tran. No.	Sta. No.	Samp. No.	Tow Type	Depth (m)	Water Mass	Copepods						Hydrozoans and Ctenophores					Pteropods
						Calanus Hyperboreus	Calanus glacialis	Pseudocalanus minutus	Euchaeta glacialis	Metridia longa	Limnocalanus macrurus	Total Copepods	Halitholus cirratus	Aglantha digitata	Staurophora mertensi	Mertensia ovum	Spiratella helicina
						mg/m3	mg/m3	mg/m3	mg/m3	mg/m3	mg/m3	mg/m3	mg/m3	mg/m3	mg/m3	mg/m3	mg/m3
1	T1-1	120	0	9	1	1.76	10.75	14.27	0.00	0.00	39.20	70.86	0.85	0.40	0.00	0.00	0.50
1	T1-2	124	0	30	1	23.73	118.53	1.40	0.00	0.13	0.13	144.16	6.16	2.93	0.00	34.82	0.00
2	T2-1	142	0	8	1	0.22	39.83	3.19	1.10	0.33	0.88	46.00	0.00	0.00	0.00	0.00	0.11
2	T2-2	146	0	22	)	39.42	578.07	0.40	0.00	0.00	0.00	717.89	0.79	5.44	0.00	1.29	6.56
3	T3-1	79	0	9	1	0.00	0.43	0.63	0.00	0.00	11.81	12.88	11.18	7.80	0.00	0.00	2.00
3	T3-2	83	0	18	1	0.20	0.20	0.00	0.85	0.00	1.50	2.81	8.18	5.47	0.00	0.50	7.47
4	T4-1	57	0	10	1	1.68	4.52	1.26	0.00	0.00	993.65	1001.20	0.00	1.77	0.00	1.50	0.55
4	T4-2	62	0	18	1	0.00	0.01	0.11	0.00	0.00	0.33	0.47	0.00	0.04	0.00	0.08	0.01
1	T1-3	129	0	40	2	63.50	170.55	0.17	1.92	0.17	0.00	236.49	0.00	17.20	0.00	0.00	4.66
3	T3-3	87	0	35	2	43.06	4.51	0.46	0.00	0.23	0.23	48.59	4.76	3.51	0.00	1.02	2.61
4	T4-3	66	0	40	2	0.46	0.25	0.04	0.00	0.00	6.17	6.92	1.31	24.63	0.00	1.20	17.62
1	T1-4	133	0	50	3	1.04	3.48	0.08	0.12	0.00	0.04	4.93	0.00	2.93	0.00	0.89	2.26
1	T1-5	138	0	50	3	0.07	0.38	0.03	0.00	0.00	0.07	0.72	0.00	0.36	0.00	6.76	0.00
2	T2-5	150	0	50	3	0.02	1.16	0.04	0.00	0.00	0.02	1.24	0.00	0.03	0.00	21.36	0.03
2	T2-5	151	0	100	3	0.23	11.18	0.09	0.00	0.00	0.09	11.68	0.00	3.94	0.00	18.46	0.05
3	T3-4	91	0	50	3	31.16	1.42	0.09	0.00	0.09	0.28	33.04	0.00	4.08	0.00	0.15	2.88
3	T3-5	95	0	50	3	0.37	0.94	0.05	0.00	0.00	0.00	1.36	0.00	3.66	0.00	0.12	1.24
4	T4-4	71	0	50	3	0.00	0.00	0.00	0.00	0.00	0.36	0.41	1.93	4.83	0.00	0.24	2.61
4	T4-5	75	0	50	3	3.22	14.27	0.30	0.12	0.30	0.24	18.70	0.00	6.76	0.00	6.69	1.42
c	5	272	V	50		0.15	6.39	0.06	0.90	0.26	0.03	7.97	0.00	0.42	0.00	2.03	0.00
C	10	239	V	50		0.22	18.87	0.22	1.74	0.43	0.00	21.47	0.00	2.84	0.00	50.05	0.00
D	10	246	V	50		0.00	5.90	0.11	0.22	12.92	0.00	29.21	0.00	0.06	269.09	1.82	0.00
D	10	255	V	50		9.13	38.25	0.11	0.11	0.23	0.00	47.94	0.00	6.73	0.00	0.00	4.61
D	12	261	V	50		6.50	51.29	0.23	0.00	0.12	0.00	58.25	0.00	2.16	0.00	1.50	0.13

Table 72 (Concluded).

Tran. No.	Sta. No.	Samp. No.	Tow Type	Depth (m)	Water Mass	Mysis		Thysanoessa raschii	Sagitta elegans	Amphipods		Fish	Total Biomass mg/m <sup>3</sup>
						Mysis juveniles	Mysis littoralis			Parathemisto libellula	Boreogadus saida		
						mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>		mg/m <sup>3</sup>
1	11-1	123	0	3	1	0.00	0.00	0.00	0.11	0.00	0.00	0.00	78.41
1	11-2	124	0	30	1	0.00	0.00	4.85	1.94	0.00	0.00	11.44	222.95
2	12-1	142	0	8	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	55.53
2	12-2	146	0	22	1	0.00	0.09	0.00	5.16	1.12	0.00	2.15	776.85
3	13-1	79	0	9	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.27
3	13-2	83	0	18	1	0.00	0.00	0.90	0.00	2.66	12.93	0.00	146.86
4	14-1	57	0	10	1	4.80	0.00	0.00	0.01	0.00	0.00	0.00	035.81
4	14-2	62	0	18	1	0.00	0.00	0.00	0.98	0.51	0.00	0.00	3.99
1	11-3	129	0	40	2	0.00	0.00	0.89	20.18	13.55	2.65	0.00	317.06
3	13-3	87	0	35	2	0.00	0.00	1.39	0.48	17.63	15.77	0.00	112.65
4	14-3	66	0	40	2	0.00	0.00	0.78	0.00	5.03	18.21	0.00	81.24
1	11-4	133	0	50	3	0.0	0.00	0.00	0.00	4.54	2.20	0.00	24.73
1	11-5	138	0	50	3	0.00	0.00	0.	0.16	3.62	3.02	0.00	57.41
2	12-5	150	0	50	3	0.00	0.00	0.00	2.30	7.57	0.00	0.00	43.92
2	12-5	151	0	100	3	0.00	0.00	0.00	8.22	0.00	18.73	0.00	66.29
3	13-4	91	0	50	3	0.00	0.00	0.00	2.49	6.51	9.69	0.00	68.11
3	13-5	95	0	50	3	0.00	0.00	0.00	0.00	3.51	1.42	0.00	18.19
4	14-4	71	0	50	3	0.00	0.00	0.00	0.00	3.76	1.94	0.00	21.26
4	14-5	75	0	50	3	0.00	0.00	0.00	28.31	1.13	0.51	0.00	65.13
C	5	272	Y	50		0.00	0.00	0.19	1.74	0.00	0.00	0.00	15.00
C	10	239	Y	50		0.00	0.00	0.00	22.53	0.00	0.00	0.00	97.21
D	10	246	Y	50		0.00	0.00	1.61	19.73	0.00	0.00	0.00	328.18
D	10	255	Y	50		0.00	0.00	2.48	9.58	0.00	8.55	0.00	85.67
D	12	261	Y	50		0.00	0.00	0.38	6.72	0.47	0.00	0.00	164.81

1 Tow type: H= Horizontal, U= Oblique, V= Vertical

2 Water Mass: 1 = Nearshore, 2 = Inner Shelf, 3 = Outer Shelf

Table 73. Raw biomasses (mg/m<sup>3</sup>) for horizontal bongo net tows at depth collected in the Alaskan Beaufort Sea in September 1986.

Transect	Sta. No.	Samp. No.	Tow Depth (m)	Sta. Depth (m)	Water Masses			Zoopl. <sup>3</sup>			Fish					Hydrozoans+		Ctenophores mg/m <sup>3</sup>	Cheatognaths mg/m <sup>3</sup>	Decapod Larvae mg/m <sup>3</sup>	Other Taxa mg/m <sup>3</sup>	Detritus mg/m <sup>3</sup>	Total- mg/m <sup>3</sup>			
					2= IS	3= OS	2= PYC.	2= out	3= AW.	4= BSW.	Copepods mg/m <sup>3</sup>	Pteropods mg/m <sup>3</sup>	Mysids mg/m <sup>3</sup>	Euphausiids mg/m <sup>3</sup>	Amphipods mg/m <sup>3</sup>	Larvae mg/m <sup>3</sup>	Copepods mg/m <sup>3</sup>									
																								1= NS <sup>1</sup>	1= SL <sup>2</sup>	1= In
1= NS <sup>1</sup>	1= SL <sup>2</sup>	1= In																								
1	1	121	10	10	1	1	1	68.89	0.00	1.58	0.00	3.56	0.19	1.16	1.20	0.39	1.69	78.66								
4	1	58	4	12	1	1	1	1006.91	0.37	9.21	0.00	0.00	1.56	10.92	0.00	5.17	0.42	1034.56								
1	1	122	5	10	1	1	2	73.76	1.24	0.00	0.00	1.55	0.00	1.86	0.39	0.42	0.76	79.90								
2	1	144	5	10	1	1	2	31.58	0.43	1.30	0.00	2.69	3.08	3.64	0.00	5.11	0.75	48.59								
2	2	148	6	26	1	1	2	6.47	0.44	0.00	0.00	0.13	9.71	1.40	0.02	2.74	0.21	21.12								
3	1	81	6	13	1	1	2	2.05	1.89	0.00	0.00	0.0	5.08	14.32	0.00	2.45	1.18	26.99								
2	1	143	8	10	1	2	1	33.47	1.06	15.21	0.38	3.23	13.40	6.42	0.00	20.94	0.85	94.96								
3	1	80	10	13	1	2	1	18.80	14.47	1.66	0.49	4.35	6.56	8.31	0.32	18.52	4.33	78.02								
4	1	60	10	12	1	2	1	219.81	0.34	5.79	0.21	5.98	11.47	41.32	7.58	1.64	1.96	296.10								
3	2	84	18	21	1	2	2	82.77	0.13	1.76	3.36	3.12	6.76	12.22	1.25	0.58	2.90	114.87								
3	2	85	10	21	1	2	2	2.44	3.64	0.34	0.55	6.31	21.70	6.40	0.37	5.15	3.95	50.85								
4	1	59	8	12	1	2	2	19.25	0.05	0.81	0.00	1.12	0.00	15.10	1.24	0.76	1.15	39.48								
4	2	64	10	21	1	2	2	52.70	3.54	0.05	0.00	1.64	0.00	21.15	3.43	1.23	1.18	84.93								
2	2	147	15	26	1	3	1	1072.83	0.87	9.87	2.43	3.20	1.05	6.79	8.11	1.71	0.82	1107.69								
4	2	63	19	21	1	3	1	1075.74	0.16	4.08	14.97	12.78	2.27	20.40	8.97	1.04	0.62	1141.03								
1	2	125	10	34	1	2	1	193.64	0.00	0.00	1.99	2.79	4.21	42.82	1.96	2.37	0.35	250.1								
1	2	126	21	34	1	3	1	153.17	0.00	1.06	2.59	3.75	4.57	19.16	13.19	0.74	4.56	202.79								
1	2	127	5	34	1	2	2	2.84	0.02	0.00	0.00	0.57	2.07	15.44	0.02	14.37	0.95	36.27								
4	3	6	9	7	4	2	1	3.77	10.16	0.00	0.00	1.10	2.19	3.76	0.01	0.33	0.23	21.55								
4	3	67	14	43	2	2	1	3.46	31.62	0.00	0.00	16.21	10.78	18.33	0.41	1.72	0.39	82.93								
1	3	131	11	47	2	2	2	8.61	2.73	0.00	0.00	3.11	2.20	10.10	0.40	0.92	0.97	29.05								
1	3	130	27	47	2	3	1	643.34	3.79	0.00	7.33	31.01	8.16	10.95	21.90	0.47	3.72	730.67								
3	3	88	26	41	2	3	1	193.64	0.37	0.14	2.18	3.47	7.18	40.00	5.95	0.75	0.66	254.33								
3	3	89	17	41	2	3	1	81.55	11.49	0.00	0.37	21.55	11.82	35.14	0.69	2.14	16.26	181.01								
4	3	68	36	43	2	3	1	177.22	0.28	0.00	0.84	2.22	0.00	6.65	3.40	0.73	0.45	191.78								
1	4	135	19	54	3	1	1	5.18	13.83	0.00	0.00	5.83	0.00	65.42	1.10	0.22	6.34	97.92								

ZOOPLANKTON BIOMASSES FROM OPENING  
AND CL. O. N. G. BO. N. GO. TOWS, 1986

## APPENDIX 2

Table 73 (Continued).

Transect	Sta. No.	Samp. No.	Tow Sta.				Water Masses		Zoopl. <sup>3</sup>		Fish				Hydrozoans+		Decapod		Other		Total- Detritus mg/m <sup>3</sup>
			Depth	Depth	Depth	Depth	Horizontal	Vertical	Layer	Copepods mg/m <sup>3</sup>	Pteropods mg/m <sup>3</sup>	Mysids mg/m <sup>3</sup>	Euphausiids mg/m <sup>3</sup>	Amphipods mg/m <sup>3</sup>	Larvae mg/m <sup>3</sup>	Ctenophores mg/m <sup>3</sup>	Chaetognaths mg/m <sup>3</sup>	Larvae mg/m <sup>3</sup>	Taxa mg/m <sup>3</sup>		
			3=	OS	3=	OS	1=NS <sup>1</sup>	1=SL <sup>2</sup>	1=in												
			2=	IS	2=	PYC.	2=out	3=AW.	4=BSW.												
1	4	136	11	54	3	1	2	3.15	0.23	0.00	0.00	0.98	2.22	2.70	0.06	0.03	1.84	11.21			
1	5	139	15	118	3	1	2	0.29	0.00	0.00	0.00	3.22	6.28	33.21	0.04	0.00	0.22	43.25			
4	4	73	12	53	3	2	1	9.89	0.54	0.00	0.00	8.31	9.01	11.02	0.12	0.26	0.31	39.46			
2	5	153	10	150	3	2	2	0.41	0.00	0.00	0.00	8.33	0.37	32.33	0.17	0.01	13.16	54.77			
3	4	92	26	53	3	3	1	156.55	0.44	0.00	2.84	34.22	4.38	17.94	37.38	0.00	8.66	262.40			
3	4	93	17	53	3	3	1	4.47	2.43	0.00	0.00	11.27	12.92	36.12	1.07	0.04	3.63	71.96			
4	4	72	34	53	3	3	1	398.27	0.10	0.00	4.34	5.77	1.78	5.83	2.17	0.11	1.08	419.46			
4	5	76	51	180	3	3	1	1.48	0.02	0.00	0.00	0.45	0.00	5.44	5.29	0.05	0.07	12.79			
4	5	77	30	180	3	3	1	3.75	0.06	0.00	0.00	1.52	0.75	10.25	21.93	0.00	0.24	38.50			
1	4	134	34	54	3	4	1	61.72	0.53	0.00	1.25	27.82	7.05	28.14	28.28	1.07	4.32	160.15			
1	5	140	47	118	3	4	1	0.12	0.06	0.00	0.00	0.69	1.09	33.07	0.1	0.00	0.07	35.21			
2	5	152	50	150	3	4	1	2.94	0.02	0.00	0.00	1.34	5.86	9.28	3.04	0.92	0.31	22.88			
3	5	97	27	205	3	4	1	0.53	0.26	0.00	0.00	6.19	4.89	33.60	0.18	0.03	1.29	344.97			
3	5	9a	30	205	3	4	1	0.42	0.20	0.00	0.00	6.89	0.00	5.02	0.44	0.15	4.23	17.34			
WF <sup>4</sup>	1	5	4	17	1	1	2	0.96	1.01	0.00	0.00	0.40	0.00	7.65	0.00	4.24	0.09	13.54			
WF	1	3	13	17	1	2	1	11.02	0.71	0.00	0.00	7.94	1.76	8.81	2.5	4.44	0.89	38.08			
WF	5	20	10	14	1	2	1	1501.13	0.00	2.44	0.16	1.52	21.97	24.37	1.93	1.67	2.83	1558.02			
WF	5	21	6	14	1	2	1	613.26	0.29	0.00	0.00	2.42	24.16	7.27	2.81	2.14	1.66	654.01			
WF	7	28	7	11	1	2	1	505.46	0.04	107.61	0.00	4.57	12.03	13.75	0.89	0.96	0.04	645.36			
WF	7	29	8	11	1	2	1	1073.12	0.00	390.27	0.00	4.13	9.98	10.01	0.00	0.17	0.00	1487.67			
WF	10	41	11	12	1	2	1	1479.67	0.00	61.68	5.86	5.66	15.88	23.78	6.95	6.44	1.88	1607.80			
WF	10	42	8	12	1	2	1	1924.90	0.00	0.12	7.27	2.85	10.74	22.60	5.26	5.43	3.66	1982.33			
WF	12	49	3	22	1	2	1	322.97	0.36	11.29	0.00	19.97	0.00	26.02	7.05	1.75	3.42	392.82			
WF	12	50	6	22	1	2	1	302.98	0.37	8.07	0.00	1.70	2.40	1.61	0.97	0.17	0.69	318.95			
WF	12	51	15	22	1	2	1	1048.48	0.00	29.77	0.29	14.00	0.00	5.18	2.64	0.00	1.19	1101.54			
WF	1	4	8	17	1	2	2	1.16	3.40	0.00	0.00	9.97	3.21	15.84	0.00	3.13	1.77	38.49			



Table 73 (Concluded).

Transect	Sta. No.	Samp. No.	Depth (m)	Water Masses				Zoopl. <sup>3</sup>			Copepods mg/m <sup>3</sup>	Pteropods mg/m <sup>3</sup>	Mysids mg/m <sup>3</sup>	Euphausiids mg/m <sup>3</sup>	Amphipods mg/m <sup>3</sup>	Larvae mg/m <sup>3</sup>	Fish mg/m <sup>3</sup>	Hydrozoans+ mg/m <sup>3</sup>	Ctenophores mg/m <sup>3</sup>	Chaetognaths mg/m <sup>3</sup>	Decapod Larvae mg/m <sup>3</sup>	Other Taxa mg/m <sup>3</sup>	Total- Detritus mg/m <sup>3</sup>		
				Sta. No.	Depth (m)	2= IS	3= OS	1= NS <sup>1</sup>	2= PYC. 3= AW. 4 = BSW.	1= SL <sup>2</sup>														2= out	1= in
WF	10	40	7	12	1	2	2	19.50	0.50	0.40	0.00	0.20	0.00	12.57	0.34	0.44	1.34	35.29							
WF	7	30	3	11	1	2	2	33.56	0.00	1.13	0.00			9.97	0.00	0.00	1.04	48.90							
CTL	8	33	17	23	2	2	1	570.89	0.23	11.29	2.72	3.26	0.30	34.47	23.02	1.70	1.82	659.80							
CTL	11	45	12	15	1	2	1	414.73	0.00	86.89	4.40	2.50	20.47	45.82	13.49	2.62	1.41	592.32							
CTL	13	54	17	25	2	2	1	3.89	0.56	0.00	0.00	1.63	7.73	29.11	0.91	8.06	2.00	53.90							
CTL	6	2	5	8	2	2	"	0.36	6.44	0.00	0.00	1.40	20.15	4.98	0.07	15.20	1.74	50.35							
CTL	8	34	7	23	2	2	2	8.98	3.11	0.00	0.00	8.59	9.69	19.93	0.28	3.44	3.04	57.06							
CTL	11	46	6	15	1	2	2	51.72	2.55	0.21	0.00	1.79	16.68	37.96	1.50	16.79	4.80	133.99							
CTL	1	3	5	5	8	2	S	2	4.21	0.91	0.00	0.00	2.98	5.19	12.68	0.09	27.12	2.24	55.42						
CTL	2	8	22	25	1	3	1	64.60	0.05	0.00	0.15	2.64	6.30	22.33	9.32	0.10	4.34	109.82							
CTL	6	2	4	2	1	2	7	2	7.63	2.31	0.28	0.28	8.43	6.77	11.19	3.77	4.36	2.49	47.51						
CTL	2	9	10	25	1	3	2	95.36	0.13	0.00	0.00	2.87	14.23	15.93	0.64	1.06	1.00	131.22							

1 Horizontal Water Masses: NS= Nearshore, IS= Inner Shelf, OS= Outer Shelf.

2 Vertical Water Masses: SL= Surface layer above pycnocline, PCY= Within pycnocline, AW= Arctic Water, BSW= Bering Sea Water.

3 Zooplankton Layer: 1= Within zooplankton layer, 2= Outside zooplankton layer.

4 WF= Whale Feeding, CTL= Control Station.

Table 74. Scaled biomasses (mg/m<sup>3</sup>) for horizontal bongo net tows at depth collected in the Alaskan Beaufort Sea in September 1986.

Transect	Sta. No.	Samp. No.	Tow Depth (m)	Sta. Depth (m)	Water Masses		Layer	Horizontal Vertical Zoopl. <sup>3</sup>																
					1 = NS <sup>1</sup>	2 = IS		1 = SL <sup>2</sup>	2 = PYC. 1=in	3 = AW. 2=out	4 = BSW.	Scaled Copepods	Scaled Pteropods	Scaled Mysids	Scaled Euphausiids	Scaled Amphipods	Scaled Larvae	Scaled Fish Hydrozoans+	Scaled Ctenophores	Scaled Chaetognaths	Scaled Decapod Larvae	Scaled Other Taxa	Scaled Total -	
					3 = OS							mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>	
1	1	121	10	10	1		1					139.64	0.00	1.67	0.00	3s	1	0.21	3.12	1.27	1.82	1.35	1	52.60
4	1	58	4	12	1		1					1943.5s	1.28	9.28	0.00	0.00	0.00	1.68	27.99	0.00	22.96	0.322	007.05	
1	1	122	5	10	1		2					141.79	4.27	0.00	0.00	1.4s	0.00		4.75	0.31	1.86	0.58	155.01	
2	1	144	5	10	1		2					56.23	1.37	1.21	0.00	2.33	3.06		8.61	0.00	20.93	0.53	94.26	
2	2	148	6	26	1		2					12.63	1.54	0.00	0.00	0.12	10.56		3.63	0.02	12.30	0.16	40.97	
3	1	81	6	13	1		2					3.21	5.31	0.00	0.00	0.01	4.44		29.82	0.00	8.84	0.73	52.36	
2	1	143	8	10	1		1					56.27	3.19	13.34	0.33	2.64	12.56		14.33	0.00	80.99	0.56	184.22	
3	1	50	10	13	1		2	1				26.54	36.57	1.37	0.36	2.99	5.16		15.58	0.24	60.14	2.42	151.36	
4	1	60	10	12	1		2	1				426.25	1.18	5.86	0.21	5.64	12.40		106.41	7.67	7.32	1.50	574.43	
3	2	84	18	21	1		2	2				167.20	0.47	1.85	3.84	3.06	7.61		32.78	1.32	2.70	2.32	222.85	
3	2	85	10	21	1		2	2				5.16	13.77	0.37	0.61	6.48	25.56		17.96	0.41	25.03	3.30	98.65	
4	1	59	8	12	1		2	2				34.12	0.16	0.75	0.00	0.97	0.00		35.55	1.15	3.10	0.81	76.59	
4	2	64	10	21	1		2	2				93.33	11.23	0.05	0.00	1.41	0.00		49.74	3.17	5.01	0.83	164.76	
2	2	147	15	26	1		3	1				2094.98	3.04	0.06	2.48	3.04	1.14		17.61	8.26	7.68	0.632	148.92	
4	2	63	19	21	1		3	1				2111.32	0.56	4.18	15.33	12.19	2.48		53.17	9.19	4.70	0.482	213.60	
1	2	125	10	34	1		2	1				358.83	0.00	0.00	1.92	2.51	4.3s		105.38	1.89	10.10	0.26	485.25	
1	2	126	21	34	1		3	1				308.88	0.00	1.11	2.72	3.67	5.13		51.26	13.86	3.43	3.63	393.41	
1	2	127	5	34	1		2	2				3.43	0.04	0.00	0.00	0.33	1.39		24.77	0.01	39.93	0.45	70.36	
4	3	69	7	43	2		1	2				5.33	25.72	0.00	0.00	0.76	1.73		7.06	0.01	1.07	0.13	41.81	
4	3	67	14	43	2		2	1				5.42	88.75	0.00	0.00	12.35	9.42		38.16	0.34	6.20	0.24	160.88	
1	3	131	11	47	2		2	2				15.00	8.5	1.00	0.00	2.63	2.14		23.36	0.36	3.69	0.67	56.36	
1	3	130	27	47	2		3	1				1298.88	13.70	0.00	7.72	30.44	9.18		29.36	23.07	2.18	2.971	417.50	
3	3	88	26	41	2		3	1				368.30	1.26	0.14	2.16	3.21	7.61		101.04	5.90	3.28	0.50	493.40	
3	3	89	17	41	2		3	1				161.10	40.64	0.00	0.38	20.70	13.01		92.19	0.71	9.73	12.70	351.16	
4	3	68	36	43	2		3	1				343.95	0.97	0.00	0.85	2.09	0.00		17.14	3.44	3.26	0.35	372.05	
1	4	135	19	54	3		1	1				7.98	38.17	0.00	0.00	4.3?	0.00		133.92	0.88	0.78	3.86	189.96	

Table 74 (Continued).

Transect	Sta. No.	Samp. No.	Depth (m)	Depth 3 (m)	Water Masses			Zoopl. <sup>3</sup>	Scaled Copepods mg/m3	Scaled Pteropods mg/m3	Scaled Mysids mg/m3	Scaled Euphausiids mg/m3	Scaled Amphipods mg/m3	Scaled Larvae mg/m3	Scaled Fish Hydrozoans+ Ctenophores mg/m3	Scaled Chaetognaths mg/m3	Scaled Decapod Larvae mg/m3	Scaled Other Taxa mg/m3	Scaled Detritus mg/m3	Total
					Horizontal		Vertical													
					1 = NS <sup>1</sup>	1 = SL <sup>2</sup>	Layer													
					2 = IS	2 = PYC.	1=in													
3 = OS	3 = AW.	2=out	4 = BSW.																	
1	4	136	11	54	3	1	2	7.07	0.92	0.00	0.00	1.07	2.78	8.05	0.07	0.15	1.63	21	.75	
1	5	139	15	118	3	1	2	0.49	0.00	0.00	0.00	2.65	5.92	74.66	0.04	0.00	0.15	83.91		
4	4	73	12	53	3	2	1	21.43	2.09	0.00	0.00	8.75	10.88	31.71	0.14	1.30	0.27	7	6.55	
2	5	153	10	150	3	2	2	0.82	0.00	0.00	0.00	8.13	0.41	86.22	0.18	0.05	10.44	106.25		
3	4	92	26	53	3	3	1	354.74	1.79	0.00	3.36	37.70	5.53	53.99	44.19	0.00	7.76	509.06		
3	4	93	17	53	3	3	1	8.72	8.49	0.00	0.00	10.69	14.05	93.59	1.09	0.18	2.80	139.60		
4	4	72	34	53	3	3	1	782.71	0.35	0.00	4.45	5.51	1.95	15.22	2.23	0.50	0.84	813.75		
4	5	76	51	180	3	3	1	3.10	0.07	0.00	0.00	0.46	0.00	15.11	5.77	0.24	0.06	24.8		
4	5	77	30	180	3	3	1	9.29	0.27	0.00	0.00	1.83	1.03	33.71	28.33	0.00	0.23	74.69		
1	4	134	34	54	3	4	1	139.92	2.15	0.00	1.48	30.66	8.91	84.72	33.45	5.58	3.87	310.75		
1	5	140	47	118	3	4	1	0.18	0.16	0.00	0.00	0.51	0.92	66.41	0.09	0.00	0.04	68.31		
2	5	152	50	150	3	4	1	6.17	0.08	0.00	0.00	1.37	6.85	25.77	3.33	0.58	0.26	44.39		
3	5	97	27	205	3	4	1	0.79	0.70	0.00	0.00	4.50	4.07	658.18	0.14	0.10	0.76	669.24		
3	5	98	30	205	3	4	1	1.08	0.92	0.00	0.00	8.64	0.00	17.20	0.59	0.89	4.31	33.64		
WF <sup>4</sup>	1	5	4	17	1	1	2	0.19	2.15	0.00	0.00	0.23	0.00	12.07	0.00	11.59	0.04	26.27		
WF	1	3	13	17	1	2	1	20.00	2.31	0.00	0.00	7.01	1.78	21.23	2.38	18.54	0.64	73.88		
WF	5	20	10	14	1	2	1	2920.10	0.00	2.48	0.16	1.44	23.82	62.96	1.96	7.47	2.18	3022.56		
WF	5	21	6	14	1	2	1	1206.12	1.02	0.00	0.00	2.31	26.48	18.99	2.88	9.68	1.29	1268.78		
WF	7	28	7	11	1	2	1	1069.79	0.15	118.83	0.00	4.70	14.19	38.65	0.98	4.67	0.03	1252.00		
WF	7	29	8	11	1	2	1	2386.07	0.00	452.75	0.00	4.46	12.37	29.56	0.00	0.87	0.00	2886.08		
WF	10	41	11	12	1	2	1	2926.11	0.00	63.64	6.05	5.44	17.50	62.45	7.17	29.30	1.47	3119.13		
WF	10	42	8	12	1	2	1	3734.32	0.00	0.12	7.36	2.69	11.61	58.23	5.32	24.23	2.81	3846.69		
WF	12	49	13	22	1	2	1	642.92	1.28	11.73	0.00	19.33	0.00	68.79	7.32	8.01	2.69	762.07		
WF	12	50	6	22	1	2	1	598.33	1.31	8.31	0.00	1.63	2.64	4.22	1.00	0.77	0.54	618.76		
WF	12	51	15	22	1	2	1	2075.20	0.00	30.74	0.30	13.47	0.00	13.62	2.73	0.00	0.93	2136.99		
WF	1	4	8	17	1	2	2	2.02	10.62	0.00	0.00	6.45	3.12	36.68	0.00	12.56	1.22	74.67		

Table 74 (Concluded).

Transect	Sta. No.	Samp. No.	Tow	Sta. Depth (m)	Depth (m)	Water Masses			Scaled Copepods mg/m3	Scaled Pteropods mg/m3	Scaled Mysids mg/m3	Scaled Euphausiids mg/m3	Scaled Amphipods mg/m3	Scaled Larvae mg/m3	Scaled Fish Hydrozoans+ Ctenophores mg/m3	Scaled Cheatognaths mg/m3	Scaled Larvae mg/m3	sealed Other Taxa mg/m3	Scaled Detritus mg/m3
						Horizontal Vertical Zoopl. <sup>3</sup>													
						1 = NS <sup>1</sup>	1 = SL <sup>2</sup>	Layer											
						2 = IS	2 = PYC.	1=in											
						3 = os	3 = A W.	2=out											
WF <sup>4</sup>	10	40	7	12	1	2	2	34.13	1.57	0.37	0.00	0.17	0.00	29.22	0.31	1.77	0.93	68.46	
WF	7	30	3	11	1	2	2	64.50	0.00	1.13	0.00	2.99	0.00	25.45	0.00	0.00	0.79	94.87	
CTL	8	33	17	23	2	2	1	1128.11	0.81	11.64	2.80	11.87	1.43	90.46	23.73	7.73	1.42	1280.01	
CTL	11	45	12	15	1	2	1	867.34	0.00	94.81	4.80	2.84	23.86	127.26	14.72	12.60	1.17	1149.10	
CTL	13	54	17	25	2	2	1	5.94	1.53	0.00	0.00	1.21	6.58	59.05	0.73	28.32	1.21	104.57	
CTL	6	25	8	27	2	2	2	0.53	17.04	0.00	0.00	1.01	16.59	9.77	0.05	51.67	1.02	97.68	
CTL	8	34	7	23	2	2	2	16.61	10.30	0.00	0.00	7.72	9.99	48.95	0.27	14.64	2.22	110.70	
CTL	11	46	6	15	1	2	2	84.94	7.50	0.18	0.00	1.43	15.27	82.79	1.29	63.43	3.12	259.94	
CTL	13	55	8	25	2	2	2	5.01	1.94	0.00	0.00	1.72	3.44	20.04	0.06	74.25	1.05	107.51	
CTL	2	8	22	25	1	3	9	129.81	0.18	0.00	0.16	2.58	7.06	59.59	0.77	0.46	3.45	213.05	
CTL	6	24	21	27	2	3	1	14.72	7.98	0.28	0.28	7.91	7.28	28.67	3.80	19.35	1.90	92.17	
CTL	2	9	10	25	1	3	2	187.83	0.46	0.00	0.00	2.75	15.62	41.67	0.66	4.80	0.78	254.57	

<sup>1</sup>Horizontal Water Masses: NS= Nearshore, IS= Inner Shelf, OS= Outer Shelf.

<sup>2</sup>Vertical Water Masses: SL= Surface layer above pycnocline, PYC= Within pycnocline layer, AW= Arctic Water, BSW= Bering Sea Water.

<sup>3</sup> Zooplankton Layer: 1= Within zooplankton layer, 2= Outside zooplankton layer.

<sup>4</sup> WF = Whale Feeding Station, CTL = Control Station.

Table 75. Biomass (mg/m<sup>3</sup>) of major zooplankton groups collected in vertical and oblique tows during the 'Polar Star' cruise, October 1986.

Tran. No.	Sta. No.	Samp. No.	Tow Type	Tow Depth (m)	Sta. Depth (m)	Copepods mg/m <sup>3</sup>	Pteropods mg/m <sup>3</sup>	Mysids mg/m <sup>3</sup>	Euphausiids mg/m <sup>3</sup>	Amphipods mg/m <sup>3</sup>	Fish Larvae mg/m <sup>3</sup>	Hydrozoans+ Ctenophores mg/m <sup>3</sup>	Chaetognaths mg/m <sup>3</sup>	Decapod Larvae mg/m <sup>3</sup>	other Taxa mg/m <sup>3</sup>	Detritus mg/m <sup>3</sup>	Total mg/m <sup>3</sup>
C	10	239	Y	50	1635	21.47	0.00	0.00	0.00	0.11	0.00	52.89	22.53	0.21	0.00		97.21
C	10	240	Y	50	635	14.30	0.00	0.00	0.91	0.00	0.00	1.85	6.59	0.00	0.11		22.96
C	10	241	Y	50	635	14.96	0.17	0.00	0.00	3.78	0.00	1.78	16.96	0.00	7.04		44.70
C	5	272	Y	50	55	7.97	0.10	0.00	0.29	0.00	0.00	2.45	1.97	0.19	2.03		15.00
C	5	273	Y	50	55	5.73	0.03	0.00	0.88	0.00	0.00	0.21	4.06	0.00	0.21		10.82
C	5	274	Y	50	55	2.19	0.00	0.00	0.15	0.00	0.00	31.73	0.54	0.00	10.15		44.77
D	10	247	Y	50	781	36.74	0.03	0.00	2.15	3.13	0.00	0.85	20.46	0.00	0.49		63.85
D	10	254	Y	50	1781	8.52	0.05	0.00	0.59	0.81	0.00	32.73	3.66	0.02	0.15		46.53
D	10	255	Y	50	1781	47.94	4.61	0.00	2.67	0.42	8.55	7.97	9.70	0.00	3.82		85.67
D	10	246	Y	50	1781	29.21	0.00	0.00	2.30	2.70	0.00	271.03	21.30	0.00	1.64		328.18
D	11	256	Y	50	55	34.11	0.11	0.00	3.64	0.86	0.00	15.64	36.67	0.00	4.67		95.69
D	11	257	Y	50	55	41.29	0.12	0.00	7.74	1.94	0.00	207.97	21.47	0.00	1.76		282.29
D	12	261	Y	50	55	58.25	0.13	0.00	0.38	1.59	0.00	97.13	6.72	0.00	0.63		164.81
D	12	262	Y	50	55	52.26	0.58	0.00	0.00	0.06	0.00	4.45	4.74	0.00	0.65		62.74
D	12	263	Y	50	55	37.94	0.91	0.00	0.18	0.64	0.00	261.27	6.30	0.18	1.58		309.00
W	14	202	O	50	62	11.95	0.35	0.09	58.80	0.34	0.00	5.00	23.36	4.13	0.39		104.42
A	10	206	O	50	1434	9.06	0.25	0.00	251.93	1.18	69.57	406.78	28.83	1.49	0.39		769.48
A	8	213	O	50	278	1.04	0.35	1.43	10.17	0.74	0.00	34.00	13.04	0.00	0.46		61.22
A	8	214	O	50	278	0.73	0.77	0.00	17.84	0.01	0.00	11.60	15.47	0.10	0.10		46.62
A	5	220	Y	50	64	0.68	0.10	1.36	11.85	8.74	0.00	1009.75	1.61	0.44	0.03		1034.55
B	10	222	Y	50	2070	29.00	0.03	0.00	29.70	3.85	0.00	300.88	2.45	0.21	0.09		366.21
B	10	223	Y	50	2070	26.40	0.03	0.00	31.27	5.13	0.00	35.33	2.93	0.27	0.13		101.50
B	10	228	Y	50	2070	30.75	0.04	0.00	19.50	1.71	0.00	1.11	4.36	0.00	0.18		57.64
B	7	232	O	50	267	11.26	0.38	0.00	61.82	2.36	0.00	0.21	42.97	1.28	0.44		120.72
B	4	236	O	30	41	3.10	0.15	6.30	3.03	0.09	29.44	2.62	3.91	1.03	0.26		49.94

1 Tow Type: Y = Vertical, O = Oblique

## APPENDIX 3

## ZOOPLANKTON BIOMASSES FROM CONVENTIONAL BONGO TOWS, 1985

See Richardson (ed., 1986, p. 309-315) for more details

Table 76. Biomass ( $\text{mg}/\text{m}^3$ ) for bongo net tows collected in the Alaskan Beaufort Sea in September 1985.

Trans. No.	Sta. No.	Sta. Depth (m)	Tow Depth (m)	Tow type	Tow mass				Time	Biomass (mg/m <sup>3</sup> )										Hydrozoa				Fish		Crustacea		Other Taxa		
					Horiz. 1-15	Vert. 1-15	2-15	3-15		Total	Copepods	Pteropods	Myxids	Euphausiids	Amphipods	Larvae	Phores	Hydrozoa	Crustacea	Crustacea	Crustacea									
1	1	2	10	13	H	1	3	1	4	9	85	1519	463.4	344.5	0.7	7.2	58.4	4.7	0.8	34.3	8.4	4.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
1	1	3	1	13	H	1	1	2	4	9	85	1600	130.6	116.8	0.1	0.0	0.2	1.9	0.0	7.3	0.2	4.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	2	6	14	28	H	2	3	2	5	9	85	1105	345.0	290.7	2.1	6.8	4.0	9.4	1.3	15.6	9.5	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	3	7	25	45	H	2	3	1	5	9	85	1232	1098.7	932.6	15.6	0.0	14.9	23.6	1.4	72.3	16.8	21.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	3	8	22	45	H	2	3	1	5	9	85	1302	170.6	124.1	2.4	0.0	2.1	7.3	1.1	25.5	4.6	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	3	9	8	45	H	2	3	1	5	9	85	1330	924.9	886.2	2.3	0.0	0.0	10.1	5.7	6.7	2.9	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	3	10	15	45	H	2	3	1	5	9	85	1348	189.1	145.2	4.1	0.0	0.0	4.6	1.7	20.9	6.3	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	3	11	0.5	45	H	2	1	2	5	9	85	1408	4.0	2.1	0.1	0.0	0.0	0.1	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	4	15	5	125	H	3	2	2	6	9	85	1255	11.5	7.3	0.2	0.0	0.0	0.1	0.1	1.0	1.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	4	16	30	125	H	3	3	2	6	9	85	1314	174.0	144.2	0.4	0.0	0.0	2.7	0.5	15.2	6.6	4.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	5	17	5	80	H	3	3	2	6	9	85	1617	16.7	4.9	0.6	0.0	0.0	1.2	0.3	6.9	1.2	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	5	18	55	80	H	3	3	1	6	9	85	1634	172.0	122.6	0.2	0.0	0.8	1.9	0.1	32.5	8.7	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	7	22	5	25	H	2	2	2	7	9	85	1406	74.9	45.3	1.4	0.0	0.0	3.9	8.2	12.5	1.1	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	7	23	16	25	H	2	3	1	7	9	85	1423	320.2	254.0	1.4	0.0	19.2	18.5	1.5	5.1	8.9	11.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	8	24	18	42	H	2	3	1	7	9	85	1541	230.4	173.2	1.5	0.0	0.1	7.9	0.2	34.8	7.7	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	8	25	12	42	H	2	3	2	7	9	85	1601	306.2	250.0	2.7	0.0	0.1	4.1	2.6	23.9	20.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	8	26	6	42	H	2	2	2	7	9	85	1617	58.7	5.8	5.2	0.0	0.0	5.9	5.3	7.1	11.2	18.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	9	30	19	56	H	3	3	1	8	9	85	1445	278.6	201.7	17.1	0.0	0.0	10.7	2.4	32.6	11.1	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	9	31	32	56	H	3	3	2	8	9	85	1516	104.6	62.9	6.4	0.0	0.0	4.9	0.7	21.9	6.4	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	9	32	9	56	H	3	2	2	8	9	85	1536	38.0	0.2	1.5	0.0	0.0	9.5	5.4	20.6	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	10	35	90	185	H	3	3	2	10	9	85	1441	46.0	33.6	0.2	0.0	0.1	1.3	0.6	5.9	3.9	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	10	36	18	185	H	3	3	1	10	9	85	1509	140.0	99.3	1.0	0.0	0.0	2.6	2.5	22.3	10.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	11	38	0.5	14	H	1	1	2	18	9	85	951	44.2	14.4	1.0	0.0	0.0	0.9	0.0	22.9	4.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	11	39	8	14	H	1	3	1	18	9	85	1007	309.8	208.6	7.7	5.9	52.1	5.1	4.1	13.6	6.9	5.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	11	40	10.5	14	H	1	3	1	18	9	85	1024	419.4	262.0	14.7	86.8	15.2	3.5	7.4	18.2	9.1	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	12	43	12	25	H	2	3	1	18	9	85	1224	414.1	376.4	1.7	0.5	0.5	3.0	12.4	10.4	5.8	3.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	12	44	20	25	H	2	3	1	18	9	85	1238	760.6	681.6	3.7	10.1	5.4	5.0	6.4	37.3	7.8	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	12	45	5	25	H	2	2	2	18	9	85	1254	33.2	11.9	3.3	0.0	0.0	0.6	9.1	3.5	2.5	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	12	46	12	40	H	2	2	2	18	9	85	1542	42.3	2.1	10.5	0.0	0.0	8.8	6.2	6.1	0.1	10.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	13	49	30	40	H	2	3	2	18	9	85	1600	82.1	48.9	2.4	0.1	2.6	5.2	12.4	4.2	1.6	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	13	50	5	40	H	2	2	2	18	9	85	1618	16.9	1.7	0.0	0.0	0.0	0.4	4.5	6.5	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1	1	10	13	O	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	2	5	25	28	O	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	3	12	35	45	O	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	4	14	80	125	O	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	5	19	50	80	O	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	7	21	22	25	O	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	8	27	39	42	O	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	9	29	50	56	O	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	10	34	100	185	O	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	11	37	10	14	O	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	12	46	20	25	O	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	13	47	35	40	O	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

a NS = nearshore (<20 m); IS = inner  
 b SL = surface layer; Pyc. = tow made within pycnocline; AW = arctic water.  
 c in = tows made within layers of zooplankton as shown on the echosounder;  
 out = tows made outside of layers.

## APPENDIX 4

MOVEMENTS OF BOWHEAD WHALES IN THE BEAUFORT SEA  
AS DETERMINED BY RADIO TELEMETRY\*Introduction

This study is one part of **an overall** study on the importance of the eastern Alaskan Beaufort Sea **to** feeding **bowhead** whales. **Specifically**, we were interested **in** determining the residence times, feeding rates and night behavior of bowheads in that part of the **Beaufort** Sea. Several aspects of this type of research require that "individual **whales** be **re-identifiable** over various lengths of time. Determination of feeding rates and surfacing patterns of individual whales--ultimately to be extrapolated to the population--requires that each be followed for several minutes, hours, or even days. To obtain residence time information, however, whales must be **re-identifiable** over wider geographical **ranges** and periods up to several weeks. Studies on other aspects of the biology of **bowheads** would also be facilitated by the ability to **re-identify** individuals.

Direct visual observations of bowheads from aircraft, ice or shore, and boats have been used to re-identify individual bowhead **whales** for studies of movement, **behavior**, and surfacing patterns (e.g. Carroll and **Smithhisler** 1980; **Würsig** et al. 1984). However, it is often difficult to be sure that a whale surfacing at one time is the same **whale** seen diving -several minutes earlier. Photo-identification of whales, for example humpback whales (**Katona et al. 1979**), minke whales (**Dorsey** 1983), and right **whales** (Payne et al. 1983), can provide verified resightings of individuals, but does not provide rapid feedback for continuous verification over short-term observations. However, photo-identification has been very useful for longer term verification of individual identification. Studies in the **Beaufort** Sea since 1981 have shown **that** many bowheads are individually identifiable in vertical photos, and have provided **within-** and between-year re-identifications (e.g. Davis **et al. 1982, 1983, 1986a,b**; this study).

Another method, radio telemetry, can **allow** continuous **re-identification** of individual **whales** over both the short and the **long** term (Watkins et al. 1978; Goodyear 1983; Mate and Harvey 1984). An important and unique aspect of radio telemetry is the ability to monitor and reidentify individual **whales** throughout the night.

Radio telemetry has been used on several large **whale** species, for example humpbacks (Watkins et al. 1978; Goodyear 1983), finbacks (Watkins et al. 1978; Goodyear et al. 1985), and gray whales (Mate and Harvey 1984; **Swartz et al. 1986, 1987**). However, the use of radio telemetry on bowhead whales has a very brief history. Hobbs and **Goebel (1982)** discuss the tagging of **two** bowhead **whales** with barnacle **tags** of **the type** described by Mate et al. (1983). One whale was monitored intermittently for about 10 min and a **second** was

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\* By Jeffrey Goodyear (Ecology Research Group, Inc.), Bernd Würsig (Moss Landing Marine Labs), and David R. Schmidt (LGL Alaska Research Associates, Inc.).

monitored--with broken signals--for about 1.5 h. Although **the** tracking of **those** whales was unsuccessful, the effort did show that radio tags can be applied to free-swimming bowhead whales. Those successful tag deployments resulted from quiet approaches, one *from a sailboat* under sail, and the other from a rowed skiff; powered approaches were not successful.

Radio telemetry was applied **in this study** in an attempt to **determine** residence **times**, feeding rates, **night** behavior, and surfacing patterns of **bowhead** whales. Although **all of** these copies (aside from **night** behavior) were **also** investigated with other **methods**, we expected that radio **telemetry could** provide valuable data if tags **could** be applied successfully to the whales. The tag **chosen** for this project was a **small 'capsule tag'** developed by the Ecology Research Group, **Inc. (Goodyear 1985)**. Although this type of tag had **not** been applied to bowhead whales before, **it** had been tested and used on fin *whales* (Goodyear et al. 1985) and was particularly successful in a gray whale study off California (Swartz et al. 1986, 1987).

### Materials and Methods

#### Study Area

The study area included *two* portions: (1) the official **study** area as defined by MMS, and (2) an additional more easterly area where we operated in order to improve the chances that whales would be radio tagged prior to the onset of their westward migration. The official study area extended from **latitude 144°W** to the eastern edge of the disputed **zone** between the U.S. and Canada. That boundary extends essentially perpendicular to the **shore** from the **coastal** location **69°38'N, and 141°00'W (Fig. 167)**. Further details of **this study area are given in the** 'Introduction' to this report. The additional area included Canadian waters east of the official study area. Radio tagging in Canadian waters was attempted only in 1986 **when** permission to radio tag was obtained from the Canadian Department of Fisheries and Oceans.

During 1985, we hoped to tag from a **13-m** boat that operated as far offshore as the 200-m **contour (50-75 km from shore)**. During 1986, a **smaller 8-m boat** was used; consequently our 1986 operations were limited to nearshore waters for **safety** reasons.

#### Field Activities

Prior to beginning any **field** activities, LGL acquired research and other permits from the U.S. National Marine Fisheries Service (permit 517); Arctic National Wildlife Refuge (1986 only); Department of Fisheries and Oceans, Canada; and the Yukon Department of **Tourism**, Heritage Branch. In addition, LGL consulted with the **Kaktovik** whaling captains and **representatives of** the **North Slope Borough**. **Also**, permission was obtained from Canadian Customs for us to enter Canadian territory, and from the Canadian Armed Forces for access to **DEW line** facilities.

In 1985, tagging and tracking efforts were to have taken place from the **13-m 'Annika Marie'**, which was also used for the plankton and water sampling work. That year, the **'Annika Marie'** was used to search for **bowhead** whales in the official study area with plans to tag and monitor feeding whales when and



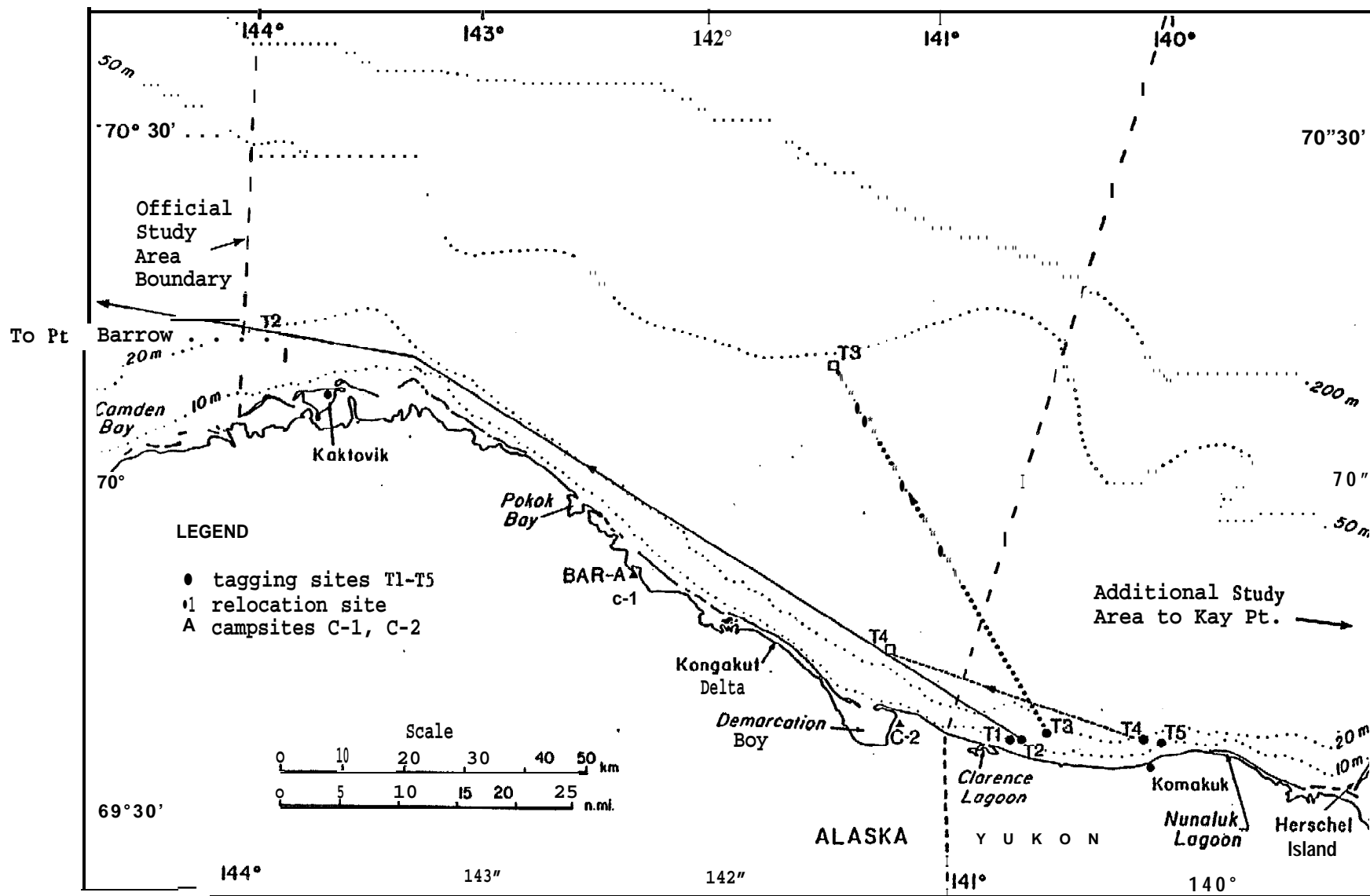


FIGURE 167. Study area, tagging sites for whales T1-T5 (solid dots), and possible routes of tagged whales. Limited work extended east to Kay Point, near 69°18'N, 138°20'W.

if encountered. Due to the lack of bowhead whales within the official study area in early-mid September 1985 (see 'Bowheads' section), no telemetry work was done from the 'Annika Marie' in 1985. Hence, reference to that vessel will be limited in the rest of this Appendix.

It was recognized that tagging opportunities would be improved if a vessel dedicated to tagging were available. In 1986, an 8-in aluminum Munson, a flat-bottom vessel powered by twin 185 hp Johnson outboards, was provided by MMS and NOAA for this purpose. The Munson was available for telemetry work from 9 September 1986 onward (Table 77). The Munson's wheelhouse was too small for overnight operations. Consequently, attempts at night tracking of whales had to be done from base camps. For the first seven days of the field stay, we utilized building at an abandoned U.S. Distant Early Warning facility (BAR-A) in Beaufort Lagoon (Fig. 167). On 17 September, we moved to a tent camp on the eastern shore of Demarcation Bay (Fig. 167). At each camp, a Telonics Inc. TR-2 telemetry receiver and a five-element Yagi-Uda antenna were set up in order to monitor tagged whales while we were ashore.

In both years, 3 or 4 DHC-6 Twin Otter aircraft plus a 'Turbo Goose aircraft, each of which was in use for bowhead studies, were equipped with telemetry antennae and receivers. The Twin Otter used by LGL for this project was equipped with two side-pointing three-element A.F. Antronics, Inc., Yagi-Uda antennas aimed about 20 degrees below the horizontal and linked to 1-4 Telonics TR-2 telemetry receivers. An operator (Bernd Würsig) monitored one or two radio frequencies at a time while the aircraft was conducting aerial surveys and reconnaissance. During three flights on 26-27 September 1986, JG as well as BW was aboard, and four frequencies were monitored simultaneously. The operator switched the reception frequencies every 15 to 30 min when more tags than receivers were in operation. Although the Twin Otter was not dedicated to the telemetry effort, significant monitoring was done by the aircraft. The majority of the aerial monitoring was from altitudes 305-457 m while the aircraft was used for other tasks, but some monitoring was done from 1500 m altitude.

Besides the Twin Otter in use by the present project, the additional aircraft that were prepared to monitor radio tags in 1985 were the Twin Otters used by Johnson et al. (1986), Ljungblad et al. (1986c), and McLaren et al. (1986), plus the Turbo Goose of Ljungblad et al. The cooperating aircraft in 1986 were the Twin Otters of Evans et al. (in prep.) and NOSC (in prep.), and the Turbo Goose of NOSC (in prep.). The other aircraft in general surveyed more to the west (i.e. west of the Kaktovik area), and in most cases each had only one receiver. However, the aircraft used by Evans et al. employed a frequency-scanning receiver at some times. After radio tags were applied to whales in 1986, aerial monitoring by these cooperating groups was done on an opportunistic basis while they were surveying for whales.

In 1986, two other projects funded by MMS overlapped with the present project; the principal investigators were Don Ljungblad and Bruce Mate. Prior to the arrival of our telemetry vessel, they offered our project logistical support by providing one of us (JG) aerial transportation to and from concentrations of bowhead whales in the Canadian waters. As well, they provided the use of an inflatable Mark II Zodiac from which to make tagging attempts during the first week of September 1986. Sea state and other

Table 77. Record of daily field activities of radio-telemetry crew in 1986.

Date	Activity and Location	Vessel
Before Arrival of Munson		
9/2	Boat from Prudhoe Bay to Kaktovik; then flew with Don Ljungblad to Komakuk	Annika Marie
9/3	Assisted Bruce Mate at King Pt.	Zodiac
9/4	On water for 2 h searching for bowheads north of Herschel Island	Zodiac
9/5	Assisted Bruce Mate at Stokes Pt.	
9/6	Assisted Bruce Mate at Komakuk; flew to Kaktovik	Zodiac
After Arrival of Munson		
9/7	Munson travelled from Prudhoe Bay to Kaktovik	
9 / 8	Munson delayed at Kaktovik by mechanical problems	
9/9	Travelled to BAR-A from Kaktovik; set up camp	Munson
9/10	Off Demarcation Bay; 2 h on water; refueled	Munson
9/11	East of Demarcation Bay; searched and made approaches to bowheads; 2 strikes with modified tag--did not penetrate	Munson/Kayak
9/12	10 km east of Demarcation Bay; made searches and approaches	Munson/Kayak
9/13	Departed BAR-A but fuel problems so returned	Munson
9/14	8 km NW of Komakuk; high sea state so returned to BAR-A	Munson
9/15	Searched to Clarence Lagoon; Tagged TW-1 and TW-2 off Clarence Lagoon	Munson/Kayak
9/16	Searched to Clarence Lagoon; some approaches until fuel problems developed	Munson/Kayak

Continued. . .

Table 77. Concluded.

Date	Activity and Location	Vessel
<b>After Arrival</b> of Munson (Cont.)		
9/17	Relocated camp <b>to</b> Demarcation Bay due to long distance from BAR-A <b>to whales</b>	Munson
9/18	Fogged <b>in</b> for most of day; departed late <b>in</b> Zodiac and tagged TW-3 4 km <b>ESE</b> of <b>Clar.</b> Lag.	Zodiac
9/19	Tagged TW-4 3 km <b>N</b> of <b>Komakuk</b> ; returned to camp to test tags in blubber	<b>Munson/Zodiac</b>
9/20	Tagged <b>TW-5</b> 3 km NE of <b>Komakuk</b> ; monitored tag <b>for 1.5 h until</b> hit by sudden storm and went to <b>Nunaluk</b> Lagoon for shelter	Munson/Kayak
9/21	Stranded at <b>Nunaluk</b> Lagoon; monitored for <b>TW's</b> <b>for 4 h</b>	Munson
9/22	<b>Travelled</b> from <b>Nunaluk</b> Lagoon west to camp at <b>Demarcation</b> Bay; saw <b>no whales</b>	<b>Munson</b>
9/23	Shore day due to bad weather; monitored for TW'S	
9/24	Shore day due to weather; monitored <b>for TW's</b>	
9/25	<b>Travelled</b> from Demarcation Bay <b>to Kaktovik</b> with engine problems	Munson
9/26	<b>Travelled</b> from <b>Kaktovik</b> to <b>Prudhoe</b> Bay with engine problems .	Munson

logistical constraints restricted our tagging attempts during this cooperative effort to parts of two days.

### Radio Tags

We used capsule radio tags (**Fig. 168**) designed by J. Goodyear of Ecology Research Group, Inc. The frequencies were 148.00 to 149.00 MHz. Each tag incorporated either a **Telonics**, Inc., or an L. and L. Electronics, Inc., telemetry transmitter of 12 or 4 milliwatts output, respectively. Transmitted pulse widths were approximately 100 milliseconds and pulse repetition rates ranged from 90 to 160 pulses per minute. Fitted to each transmitter was a 1/4 wavelength whip antenna 1 mm in diameter by approximately 45 cm long.

Tag housings were stainless **steel**, torpedo shaped cylinders with four small blades at the tip and six 0.5-mm diameter stainless **steel** tines mounted on the sides (**Fig. 168**). The blades protruded laterally beyond the housing diameter by only 5 mm, and were present to facilitate tag entry. Prior to the 1966 field season, the **Kaktovik** whaling captains requested that we reduce the blade size and remove the tines from at least two tags. Implications of these modifications will be discussed below. Tags were of two sizes: (1) 6.5 cm long by 1.4 cm diameter; and (2) 7.3 cm long by 1.6 cm diameter. The slightly larger housings were necessary for the **Telonics** transmitters because of their greater length and higher current drains; the greater amp/h batteries required for the **Telonics** transmitters necessitated the additional housing space. Tags equipped with a **Telonics** transmitter had projected signal lifetimes of 16 to 30 days. Some of the L. and L. **Electronics** transmitters were also installed in the larger housings with large batteries; these had projected signal lifetimes of up to 120 days.

### Deployment of Tags

The trailing end of each capsule tag was machined to provide a mild press fit with a hollow fiberglass archery arrow. An arrow was pressed into a tag with the antenna inside the arrow. Perpendicular to the long axis of the arrow was a restrictor pin that limited the capsule tag's depth of penetration into a whale to less than 10 cm (**Fig. 169**). Blubber thickness on the dorsal surface of a bowhead whale is about 25-40 cm. Hence the tags did not penetrate into the muscle layer. A 2-kg test fishing line kept the tag and arrow tightly together and prevented tag-arrow separation upon poor deployment or a missed shot. A 9-kg test fishing line tethered the arrow to a fishing reel mounted on a 60-kg pull **Barnett** crossbow. Tags that missed a whale, or achieved only shallow penetration, were retrieved by reeling them in. Prior to deployment, the tag and arrow were prepared, loaded into the crossbow, and rinsed with alcohol for sterilization.

Two vessels were used for deployment approaches. Rapid motor-powered approaches took place from a Mark 11 Zodiac inflatable with 25 hp Evinrude outboard. Slow quiet approaches were made with a 5.2-m **Klepper** two-man sea kayak. The kayak was modified so that the tagger could sit on a board placed above the forward seat across the gunwales. This raised the tagger by about 40 cm.

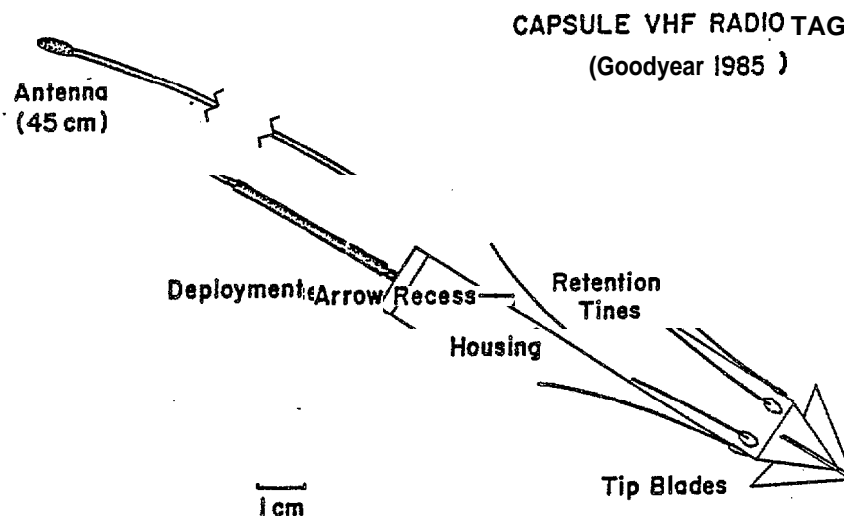


FIGURE 168. Capsule radio tag used on bowhead whales in this study.

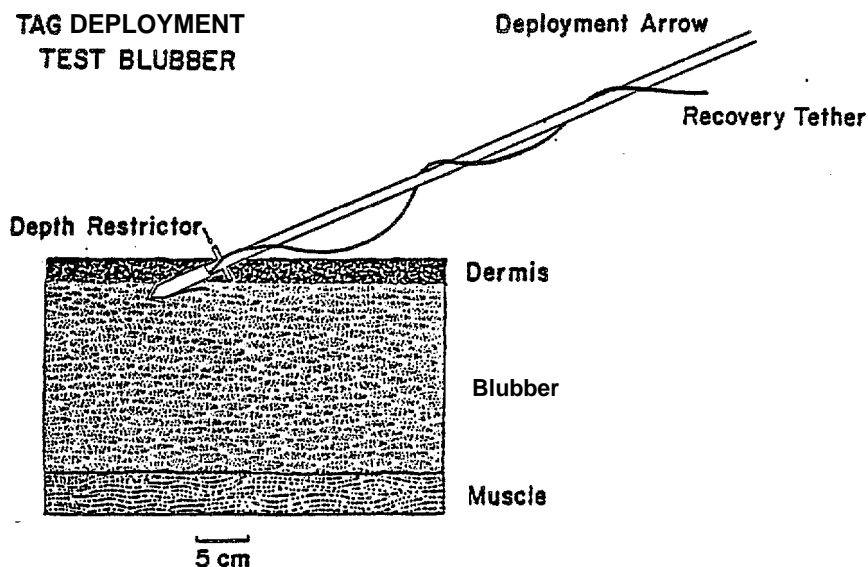


FIGURE 169s Tag and arrow deployed into bowhead blubber removed from a location 50 cm laterally from the blowhole of a 17 m bowhead (1986 KK2). Note arrow penetration restrictor pin and tag recovery tether.

### Boat-Based Radio Tracking

Radio tracking gear was set up aboard the 'Annika Marie' prior to embarking on field activities on 3 September, 1985. A similar installation was established aboard the Munson in 1986. An aluminum pole fitted with a compass degree wheel and a three element **A.F. Antronics, Inc., Yagi-Uda** antenna passed through the cabin roof and extended to 8 m above the sea surface. The elements of the antenna were oriented perpendicular to the sea surface. The antenna was linked to a **Telonics, Inc., TR-2** telemetry receiver tuned for the 148.00 to 149.00 MHz band. Signals received by the receiver were audible as beeps, searing from the receiver to the radio tag, i.e. to a tagged whale, was determined by rapid panning back and forth of the rotatable antenna pole until the strongest signal was heard.

Radio signal and observation data were recorded on a Radio Shack TRS80-100 portable computer and/or by dictation into a portable cassette recorder. A BASIC language program was written to prompt the user for entries when radio signals were heard, i.e. when a tagged whale surfaced.

### Aircraft-Based Radio Tracking

Transmitters were monitored from the LGL project Twin Otter by a three element **A.F. Antronics Yagi-Uda** antenna mounted on each wing strut. Both antennas were linked, through appropriate impedance matching devices, to as many as four **Telonics TR-2** telemetry receivers. A switching system allowed for monitoring up to four signals at a time, and the rapid elimination of unwanted frequencies once a signal was received on one frequency. The majority of aerial monitoring was from altitudes 305-457 m while the aircraft was used for other tasks, but some monitoring was done from 1500 m altitude. A total of 27 hours was spent monitoring for whale tags from the LGL project aircraft (Table 78). We monitored for two capsule tags applied to bowheads by B. Mate on 15 September 1986 as well as for the five tags applied during this project. An unknown number of additional hours was spent monitoring from the aircraft engaged in other projects,

## Results

### Field Time

In 1985, the 'Annika Marie' conducted eight days of zooplankton and water sampling, during which time we searched for bowheads. Only one bowhead whale was seen from the 'Annika Marie' in 1985. This occurred on the day of departure for Prudhoe Bay under threatening ice conditions.

In 1986, a total of 37 hours spread over eight days represented our boat crew's total sea time for searching, tagging, and monitoring bowheads (Table 77, 79). That total excludes many hours spent in transit aboard the Munson from BAR-A (Fig. 167) to the Yukon coast where most of the whales were found. It also excludes the limited time spent with B. Mate's crew in early September prior to the arrival of the Munson.

Table 78. Aerial monitoring effort for radio tagged bowhead whales, 16-27 September 1986.

Date Sept	in '86	Time (ADT)	Tag(s)	Airplane Altitude (m)	Area Scanned	Result
16		09:15- 11:26	12, 14	457	Kaktovik to Komakuk, about 5 km offshore	NS
		12:28- 12:50	12, 14	1524	Komakuk to Kaktovik, about 5 km offshore	NS
17		09:40- 09:50	14	1524	About 30 km east of Kaktovik	NS
19		09:47- 10:00	4, 12, 14	457	Kaktovik to Pokok Bay about 5 km offshore	NS
		10:00- 10:43	4, 12, 14	457	Pokok Bay north to 70°33'N, 142°26'W; return to Pokok Bay	NS
		10:43- 11:20	4, 12, 14	457	Pokok Bay to Herschel Island, within 5 km of shore	NS
		13:45- 14:00	12	457	Komakuk to Demarcation Bay, within 5 km of shore	NS
		14:53- 15:25	14	457	Demarcation Bay to Kaktovik	NS
20		11:35- 12:11	14, 15	457	Kaktovik to Komakuk, 5 to 10 km offshore	NS
		13:20- 14:20	4, 14, 15	305	Aerial survey transects #1 and #2, shore to 200 m depth contour	NS
21		09:45- 12:30	4, 14, 15	Variable 914-1524	Kaktovik to Demarcation Bay, within 5 km of shore	#15 off Demarcation Bay
		12:30- 13:30	2, 14, 15	1524	Komakuk to Kaktovik, within 5 km of shore	NS
22		09:46- 10:15	2, 14, 15	Variable 457-1524	Kaktovik to Demarcation Bay, within 5 km of shore	NS

Continued. ..



Table 78. Continued.

Date in Sept '86	Time (ADT)	Tag(s)	Airplane Altitude (m)	Area Scanned	Result
22	10:15- 13:50	2, 14, 15	305	Aerial survey transects #1-8, between shore to 200 m depth contour	NS
	14:50- 16:11	2, 14, 15	305	Aerial survey transects #9-12, from shore to 200 m depth contour	NS
	16:20- 18:20	Mate 148.600, 4	457	Kaktovik to Demarcation Bay, 5 to 15 km offshore	#4 north of 69°58'N, 141°47'W
	19:25- 19:50	"4, 14, 15	1524	Demarcation Bay to Kaktovik, over coast	#4 north of coast, on or near serial transect line #9
25	13:55- 14:35	2, 14, 15	457	Kaktovik to Herschel Island, 10 to 20 km offshore	NS
	14:40- 15:30	Mate 148.600, 4		Herschel Island to Kaktovik, within 5 km of shore	NS
	15:30- 17:42	Ma 148.600, 2, 4, 14, 15	305	Aerial survey transects #13 and 21-18; then to Kaktovik	NS
26	09:50- 11:35	2, 4, 12, 14, 15	305	Aerial survey transects #17-14	NS
	14:00- 14:19	2, 4, 12, 14, 15	Variable 457-1219	Fran 70°05'N, 140°25'W to Kaktovik	NS
	15:10- 16:30	Mate 148.600, 2, 4, 14, 15	457	Kaktovik to 70°23'N, 143°30'W; then east to 70°07'N, 141°26'W	NS

Continued...

Table 78. Concluded.

Date in Sept '86	Time (ADT)	Tag(s)	Airplane Altitude (m)	Area Scanned	Result
	18:29- 18:40	Mate 148.600, 2, 4, 14, 15	609	From 70°10'N, 141°24'W to BAR-A	NS
	H:05- 19:20	Mate 148.600, 2, 4, 14, 15	609	BAR-A to Kaktovik	NS
27	12:10- 12:42	2, 4, 12, 14, 15	457	Kaktovik to 70°04'N, 140°29'W	NS
	15L38- 16:02	2, 4, 12, 14, 15	457	69°49'N, 141°30'W to Kaktovik	NS

#### Tagging Approaches

Five bowhead whales were tagged with the capsule radio tags (Table 77, 79). Three of those were tagged from the kayak and two from the Zodiac. It took much longer to approach within tagging distance (<25 m) with the kayak than with the Zodiac because it was necessary to shut down the 'Munson--the mother vessel--at least 1 km away from any whale (bowheads fled when the Munson approached]. Once the Zodiac was within a few hundred meters, the whales also fled. Thus all Zodiac approaches had to be at high speed. Two Zodiac approaches resulted in successful tag deployment, but the whales in each case had to be chased and they subsequently appeared extremely wary. No response to the actual tag deployment was distinguishable from the chase responses in that type of approach.

Eight kayak approaches with deployment attempts took place in sea states up to Beaufort Four (Table 79). These resulted in three successful tag deployments. Reactions to the kayak approaches were mild or absent except on one occasion when the kayak's momentum carried it to within approximately 4 m of a whale after tag deployment. In that case the whale dove below the kayak and avoided a collision. Two whales approached by the kayak and struck by modified capsule tags (reduced tip blade size and no tines) responded when the recovery line was jerked to pull out the arrow. One other responded when a long distance shot was made and the tag first ricocheted off the water and then landed on the back of the whale without penetrating. These responses consisted of dives that were made more rapidly than normal.

Table 79. Details of bowhead whale taggings and approaches.

Date	Time	Location	Firing Dist. (m)	Miss/Hit (M/H)	Tag #	Kayak/ Zodiac	Tag Location	Whale Reaction	Approach Speed	Distance of Approach (m)	App. Duration (min)	Est. Length (m)	Whale					Comments
													Behavior Before Approach	Behavior After Approach	No. Whales Within 50 m of TW	Sea State		
9/11	16:30	8 km NE Demarcation Bay	9	H	1M	K	2 m behind blowhole; 10 cm from midline	Rapid submerg.	Drift	50		4	12	Resting	Slow travel	0	4	Modified tag; did not penetrate
9/11	17:20	Same	10	H	1M	K	2 m behind blowhole; 1 m down right side	Same	Slow paddle	20	0.5	10	Travel at 2 km/h	Travel at 2 km/h	0	4	Same as above	
9 / 13	14:09	2 km NE of Clarence Lagoon	55	H	14 TW1	K	30 cm down right side snout	No reaction	Medium paddle	40	1	U	Slow travel	Stopped then slow travel	0	2	Solid hit; antenna out 180°	
9/15	15:00	Same	16	M	12	K	N.A.	No reaction	Slow paddle	111	2	14	Slow travel	Slow travel	1	2	Associated whale; Sim. size	
9/15	16:00	Same	13	M	12	K	N.A.	Rapid dive	Medium paddle	m	2	13	Slow travel	Slow travel	0	2	Shot was slight graze	
9/15	16:38	Same	u	H	12 TW2	K	30 cm down left side snout	No reaction	Fast paddle	103	1.5	U	Slow travel	Slow travel	0	2	Recovered broken arrow tip	
9/15	17:30	Same	17	M	4	K	Grazed dorsum 3 m aft of blowhole	Rapid dive	Medium paddle	60	1	13	Slow	Slow	0	2	Landed on back of whale	
9/18	18:00	4 km ESE Clarence Lagoon	6	H	4 TW3	Z	4 m aft of blowhole on dorsum	Reaction not discern.	Fast motor	100	0.3	U	Medium travel	Rapid travel	0	3	Chase caused flight of TW	
9/19	16:00	3 km N of Komakuk	5	u	15 TW4	Z	4 m aft of blowhole on dorsum	No reaction discernable	Fast motor	130	1.5	12	Slow travel	Rapid travel	0	1	Chase caused flight	
9/20	17:05	3 km NE of Komakuk	7	N	2 TW5	K	30 cm down on right side	No reaction	Slow paddle	30	1	14	Slow travel Mid water	Slow travel Mid water	0	1	Whale rolled upside down; then swam under	

Standard capsule tags with nominal length blades and tines appeared to penetrate completely during the five successful deployments. The 2-kg test fishing line from the tag to the arrow snapped on impact as planned, verifying that the tags deployed fully to the arrow stops. All taggings and approaches occurred near either Clarence Lagoon or Komakuk in Canada (Fig. 167).

### Behavior of Tagged Whales

Four of the five tagged whales were monitored for brief periods after tagging. The first bowhead whale to be radio tagged (TW-1) was tagged on 15 September 1986 and never relocated by radio tracking. Effective monitoring attempts did not begin until the kayak and tagging crew could return to the Munson nearly an hour after tagging. By that time, the tagged whale could have travelled several kilometers and might have been out of radio range, given the low antenna height on the Munson.

Four other whales were tagged: TW-2 was tagged on 15 September, about 2 km northeast of Clarence Lagoon; TW-3 was tagged on 18 September northeast of Clarence Lagoon; TW-4 was tagged on 19 September 3 km north of Komakuk; and TW-5 was tagged on 20 September 3 km NE of Komakuk at about 69°40'N, 140°13'W (Fig. 167). Each of these whales was monitored by radio on one occasion.

Monitoring of TW-2, TW-3, and TW-4 was problematic since each was relocated by radio only once after tagging. From TW-2, we received no signals at the Munson shortly after tagging despite monitoring effort's for over 1.5 h. On 1 October, 16 days later, signals from TW-2 were received at a shore station at Point Barrow, about 625 km WNW from the tagging site off Clarence Lagoon. Similarly, signals from TW-3 were not received aboard the Munson. However, on 22 September, 92 h after tagging, TW-3 was relocated in open water near 70°08'N, 141°47'W, 76 km to the NW, based on radio signals received aboard the project's Twin Otter aircraft. Whale position and distance relative to the aircraft were estimated. Observable behavior of TW-3 prior to tagging was medium speed travelling, estimated to be at 2-4 km/h. Water column feeding was suspected at the tagging site because TW-3 and other whales in the area were making wide circles of up to several hundred meters diameter; some of their dives lasted over 20 min.

Similarly, TW-4 was relocated by radio from the Twin Otter. Signals from TW-4 were received on 21 September at approximately 69°45'N, 141°20'W (Fig. 167), a straightline distance of 48 km from the tagging site. Observable behavior of TW-4 prior to tagging was slow travel, estimated as 1-2 km/h. As with TW-3, TW-4 was suspected to be water column feeding at the tagging site because of the long dive times and wide circling pattern.

Radio signals were received from TW-5 immediately after tagging and were strong and clear. Prior to tagging at 17:05 ADT, TW-5 was traveling slowly in wide circles of about 300 m diameter, with dive times of 6-8 min; we suspected that TW-5 was feeding in the water column. After tagging, no difference in the whale's behavior was noticed. By 17:53 the whale had travelled approximately 3.5 km to the SSE maintaining the wide circling behavior. After that, the whale slowly moved back toward the Munson by 0.5 km, maintaining the same behavior interspersed with some long resting periods. The total tracking period extended from 17:04 to 18:25 during which period radio signals remained

very **strong** and **clear** and the whale remained visible during **its** surfacings. Dive times ranged from 18.7 to 7.9 min as the whale progressed to its **farthest** distance from the Munson. The last dive time monitored was 21.6 min (Fig. 170). Tracking stopped when wind speed **increased** suddenly, with gusts to over 90 km/h.

Subsequent monitoring attempts included efforts from the Munson, shore stations set up at our **campsites**, and from the several aircraft. From those **efforts**, the only signals received were the previously mentioned signals from **TW-2**, TW-3, and TW-4 on 1 October, 22 September, and **21 September**, respectively.

#### Field Tests of Tags

The types of tags used in the project had been used successfully in a previous study on gray whales off California (Swartz et al. 1986, 1987). Prior to embarking on this project, **all** radio tags had been tested for proper operation after having been cooled in a freezer to approximately **-8°C**. Tags produced strong and regular signals immediately after being removed from the **freezer**--i.e. when they were **still** at **-8°C**--and they continued to do so while warming back to ambient room temperature. **Only** a slight change in signal pulse **rate** was noticed; signal pulse rate decreased slightly after being cooled **but** resumed original rates once temperature returned to ambient room temperature.

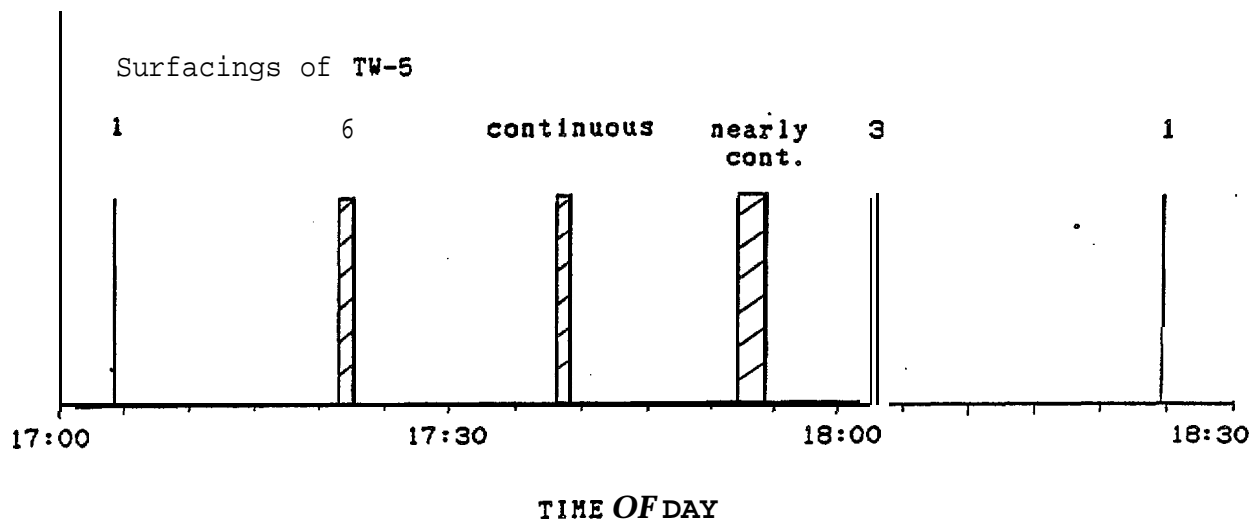


FIGURE 170. Surfacing-dive pattern of whale **TW-5** on **20** September 1986, as determined by monitoring the radio tag. Bars indicate time from first to last surfacing within each surfacing sequence; numbers above bars are numbers of surfacings per surfacing sequence.

After whale number four was tagged on 19 September 1986, serious problems either with the receiving system and/or the radio tags were suspected. Up to that time, no tags had been detected from the Munson, shore or aircraft after they were applied to whales. Hence, a series of field tests was performed to confirm earlier tests.

At the Demarcation Bay campsite, both sizes of capsule tag with both brands of transmitter were deployed from the crossbow into a 24 by 34 by 34 cm block of fresh bowhead whale blubber provided to us by the Kaktovik whalers (Fig. 169). Several test shots were made from distances bracketing typical distances during deployment attempts in the field, i.e. 5-20 m. All test shots that hit the blubber--12 out of 13--penetrated the blubber perfectly i.e. to the depth controlled by the arrow's restrictor pin. Deployment angles ranged from 45°-75° away from perpendicular to the skin surface, all with the same result. All tags penetrated and had to be carefully extracted from the blubber by cutting. We tested the effectiveness of a tag's holding power by lifting the entire 18-kg (estimated weight) block of blubber by the tag's antenna; it held without slippage or tag damage.

Throughout the test, a telemetry receiver was tuned to the frequency of each tag being fired. In all cases, tags kept transmitting clearly and strongly. One tag that contained an L. and L. Electronics transmitter was fired three times into the blubber with no change in the tag's performance. Also, all test tags were submerged in sea water for several minutes to see if any water leaks had developed; all continued to transmit well. Since these tests indicated no problems with the tags and deployment method, testing of the receiving system aboard the Munson followed,

Prior to tagging whale number five, four transmitters were carried aboard the Zodiac and taken about 2.5 km away. By VHF radio, we communicated with the Munson to verify that signals from the tags were being received. All tags produced clear signals even when they were submerged with only 10 cm of the transmitting antenna exposed above the water surface. However, these results depended on which receiving antenna was used. The hand-held H-beam Telonics, Inc., antenna, when held with its elements parallel to the water surface, allowed no signals to be received. When the H-beam was turned with the elements perpendicular to the sea surface, the signals were strong. The three element Yagi-Uda mounted to the aluminum pole produced signals only about half as strong as did the H-beam when both were optimally oriented; cabling or antenna coupling problems were suspected.

Some tags were left on the Munson and monitored on the Zodiac by a hand-held H-beam and receiver. Signal reception on the Zodiac was much better than that on the Munson, requiring a lower gain setting on the receiver.

In 1985, aerial reception tests were conducted using several tags taped low on the deck of the 'Annika Marie' while underway. Tests were under conditions of fog, obscured skies, and with the LGL Twin Otter flying at approximately 900 m altitude. Tags with Telonics transmitters were receivable from over 58 km while those with the L. and L. Electronics transmitters were receivable from about 30 km.

Reception ranges determined by these tests were as expected for tags incorporating the types of **Telonics** and L. and L. Electronics transmitters that were used. These ranges should have been adequate for relocating tagged **whales** given the extent of radio receiver coverage we had in this project.

### Discussion

#### Field Activities

**Events** in 1986 demonstrated the importance of careful planning combined with flexibility in logistical arrangements and study sites. LGL obtained all necessary permits to **allow** tagging and associated operations in both U.S. and Canadian waters, including authorization **to** enter Canadian territory without having to **travel to the nearest Customs entry point (Inuvik, N.W.T.)**. These preparations proved to be essential to our successful tagging of five whales. Our success also depended on close cooperation between boat and **'aircraft-**based crews, including good radio communications. The aircraft **crew** provided directions to whale locations, delivered fuel and supplies to remote camp locations, relocated two tagged whales, and relocated the boat crew when they were marooned away from their base camp **by a** storm. Future tagging work should include provision for similar kinds of support.

**Actual** field time for the telemetry aspects of this study was low. In **1985**, virtually no whales used the study area during the period when **boat-**based operations were possible. In 1986, **field** activities. began **late as** complications with the Munson delayed the start of actual telemetry fieldwork until 10 September. Logistical support provided by Don **Ljungblad** and **Bruce** Mate on '2-6 September 1986 was helpful by allowing **JG** to **learn** the general locations of whales and optimal procedures for tagging approaches. .

The design of the Munson, and the use of two **large** outboard engines, provided a high-speed capability that was useful under near-calm conditions. However, the high rate of fuel consumption necessitated frequent refueling at remote **fuel** caches, which took considerable time for both the Munson crew and **LGL's** aircraft crew (which ferried fuel drums to our camp locations).

The **Munson** was usable in the nearshore **areas** where bowheads concentrated in September 1986, at least under the unusually favorable weather encountered then. It was beneficial to have a dedicated vessel in 1986 rather than sharing the use of the boat used for **zooplankton sampling**. However, the Munson was not a **very** seaworthy craft, and would not be suitable for work farther offshore. One of the objectives was to determine if bowheads feed at night. However, the Munson was not equipped **to** spend the night at sea. An appropriate vessel **for** radio-telemetry work in the Beaufort Sea also needs to have reliable means of determining position, including a **Sat-Nav** and radar.

#### Interpretation of Tracking Data

Five bowhead whales were tagged and three significant radio relocations of tagged whales resulted. The 16 d relocation record of **TW-2** covered 625 km, or an average of 39 km/d or **1.6** km/h. That **rate** is slightly **less** than the minimum average speed of one bowhead photographed on two days in September 1985; it **travelled** at least 473 km in one 10 d interval (47 km/d, 2.0 km/h;

Richardson et al. 1986b, p. 190). Similarly, a mother and calf photographed on 27 September 1986 and 1 October 1986 had travelled 212 km in 4 d, i.e. 53 km/d or 2.2 km/h (Table 41). The minimum average speeds for long distance movements of these types are not directly comparable to speeds of whales at any one time (e.g. during a short feeding event or active migration), since whales are unlikely to move in a straight line for long distances and since they might stop periodically.

TW-3 averaged 20 km/d or 0.8 km/h over a 92 h period. TW-4 averaged 25 km/d or 1.04 km/h over a 46 h period. Both whales were relocated within the official study area, an area important to some bowheads for feeding as they migrate west (see 'Bowheads' section). These movement rates are similar to many of those determined by photographic re-identification (Davis et al. 1986a,b; this study).

The last tagging included some monitoring, from the Munson, of consecutive surfacings by TW-5. TW-5 was monitored from up to 3.5 km away. Signal strengths received from the tag during that period indicated that there should have been little problem receiving signals from that whale to the horizon. Given the antenna height on the Munson (8 m), the range to the horizon should have exceeded 15 km from that vessel. Regrettably, just when monitoring was going 'flawlessly', bad weather intervened. The most significant result of the tagging of TW-5 was the indication that, when all systems are working, fine-scale monitoring of surface patterns, behavior, and movements of bowhead whales is very feasible with VHF radio tags.

We returned to the Komakuk-Demarcation Bay area on 22 September after the period when we were forced to seek shelter inside Nuneluk Lagoon. By then, bowheads had left that nearshore area. Based on the three tag receptions farther west on 21 September-1 October, these whales had apparently begun their westward migration.

#### Tagging Approaches

Zodiac.--The use of the Zodiac as a platform for tagging bowheads had mixed results. TW-3 and TW-4 were approached and tagged within 20 s and 1.5 min, respectively, and with sea states of Beaufort 3 and 1, respectively. These short duration chases, although high speed and aggressive (requiring much turning), minimized the time necessary for the approach. Two other approaches with the Zodiac were not successful. On 21 September, after several minutes of high speed chasing and continued elusive maneuvering by the whales, we broke off the attempts. Those two whales rapidly left the area, raising their flukes 'high out of the water as they went. The whales may have been particularly wary because there had been Zodiac-based tagging activities by other researchers in that same area for several consecutive days just prior to our attempts. Bowheads that have not recently 'been exposed to motorboat approaches are likely to be less wary.

Use of inflatable motorboats for tagging should remain an option in future studies. However, their impact and effectiveness will vary depending on wariness of whales and the objective of the study. If the objective is to document the behavior of tagged whales in the areas of tagging, aggressive chases with resulting disturbance are unlikely to be a satisfactory method.



Kayak.--Kayak approaches appeared non-disruptive to whales. In fact, it was usually not until we had paddled to within 4-5 m of a whale that it appeared to acknowledge our presence. Another advantage is that, once within deployment range, the relative calm of the whale allowed more time for careful aim. Two things helped improve the problem of the low tag deployment angle from a kayak. One was placing a small board across the gunwales of the kayak, thus raising the tagger (JG) up by about 40 cm. The other was to approach a whale head-on and wait until it dove in front of and toward us. That position allowed the tagger to aim for the forward part of the dorsum, providing near-perpendicular deployment angles.

Although we had good sea conditions for tagging and did not use outriggers, instability of the kayak would generally be a problem without them. To stabilize the kayak, we designed two types of outriggers that we felt would have been ideal. One was an inflatable toy canoe 1.2 m long and weighing about 0.5 kg. The other type of outrigger was a shaped piece of styrofoam. These outriggers could each be mounted to a pair of aluminum poles and mounted to the kayak. We felt that this modification would allow tagging to be conducted in sea states up to Beaufort four.

### Tag Design

Studies on gray whales" (Swartz et al. 1986, 1987), humpback whales (Goodyear 1983, in prep.), and fin whales (Goodyear et al. 1985) showed that the transmitters used in the capsule tags provide adequate power for monitoring those "species throughout day and night periods. Those studies, along with the successful tagging of bowheads, in this study, showed that a crossbow can be effective for tagging large baleen whales. Recent advances in miniaturization of components will substantially increase the power output of transmitters that can be incorporated in capsule tags. Incorporation of these transmitters would significantly increase the sensitivity and range of the telemetry system and its appropriateness for bowhead studies.

Prior to the 1986 field season, the Kaktovik whaling captains requested that the tags be modified to include smaller tip blades and no tag retention tines. Tests of these modified tags prior to arrival in the field indicated that this modification would not allow the tag to penetrate blubber. Once in the field, two shots on bowheads were made with the modified tags (11 September; see Table 79). The tags barely penetrated into the blubber, and both tags were easily pulled out with the tag's recovery line. Our later tagging efforts were with the original tag design with larger tip blades plus tines (Fig. 168). Further use of the modified tags is not recommended, at least if they are to be deployed by a crossbow.

Don Ljungblad (pers. comm.) modified deployment arrows in order to deploy Ecology Research Group capsule tags by a shotgun. The shotgun was able to provide sufficient penetration power for capsule tags without tip blades. He and Bruce Mate used the shotgun system to tag two bowheads in the Komakuk area with the capsule tags during our study period. Neither of those two tagged whales were detected on subsequent dates.

The tags and crossbow deployment system were inexpensive and of simple construction. Set-up of each tag-arrow combination and loading into the crossbow took less than one minute. Prior to firing a tag, a second and

sometimes a third tag and arrow were set up so that a second or third tag deployment could be made rapidly. A simple chest pad on the tagger allowed the crossbow to be cocked easily and safely even when cocking was necessary in the kayak. The system also provided satisfactory tag deployment ranges and angles when tags were shot either from the Zodiac or the kayak.

### Monitoring Problems

In this section we outline some of the field problems that were encountered. This information is presented with the view that it may help any other investigators who attempt to tag bowheads.

Tests in 1985 of receiving range between tags on the 'Annika Marie' and a receiving system aboard the Twin Otter indicated that the telemetry system should be practical for bowhead whales. The successes of this same system when used on gray whales in January 1986 (Swartz et al. 1986, 1987) and on humpback whales (Goodyear 1983, in prep.) lend support for its application to bowhead studies. In the Swartz et al. study, we successfully monitored gray whales both from shipboard and from the air. Surfacing and dive patterns were recorded continuously throughout day-night periods in both of those studies.

Problems in monitoring tagged bowhead whales limited our success. Although 4 of 5 tags were detected at some point after deployment, only 1 of 5 was detected from the Munson, and no tag was detected on more than one day. This was probably due, in large part, to the late dates when tags were applied (15-21 September). By that time, whales apparently were about to leave their feeding area along the Yukon coast and commence westward migration. (All whales had apparently left that area by 22 September.) If logistical arrangements had allowed tags to be applied earlier, residence times and behavior probably could have been documented.

To monitor the tag before and immediately after tag deployment, it is necessary to have sufficient personnel to allow full-time tracking from the mother vessel while the tagging crew is in the kayak or Zodiac. Without this capability, a whale might move out of range before tracking commenced.

In 1986, much of the time each day was spent travelling to and from areas of whale concentration, usually at high speed and sometimes over rough seas. Cables and connectors for the telemetry antenna and receiver, and the antenna itself, are likely to incur physical damage in these conditions. These problems can be overcome by careful maintenance and testing of equipment, as demonstrated by the successful monitoring of TW-5 (prior to weather problems).

Aircraft as well as boat- and shore-based receiving systems should be frequency-matched with the specific radio tags to be used on tagged whales. Although specific frequencies were known for the tags used, and some tagged whales were detected from the aircraft, receivers from various sources may not all have been tuned optimally. Slight frequency mismatches could reduce reception range, possibly to the point that a receiver might be ineffective for locating tagged whales. To solve this potential problem, all complete receiving systems and tags should be tested and tuned in one place prior to field activities.

Given that we have demonstrated that, under favorable conditions, several bowhead whales, can be tagged within a few days, **it will** be desirable to use frequency-scanning receivers in future monitoring efforts.

### Conclusions

Approaches to bowhead whales for radio tagging were conducted readily from a quiet vessel--a kayak--and **less** easily from an outboard powered Zodiac. **In the cases of the quiet** approaches, bowheads appeared to be undisturbed and continued **their** normal behavior. Zodiac approaches required chasing and appeared to drive some whales out of the area for at least several minutes; others appeared **not** to return at all. The actual deployment of capsule. **tags** was readily accomplished with **the crossbow system**, and did not elicit **any** major reactions by the whales.

Kayak and Zodiac approaches resulted in five bowheads being tagged with capsule radio **tags**. **Three of these tags resulted in the first successful and significant radio tracking of bowhead whales. One of the tagged** whales was **relocated by radio** off Point *Barrow* 16 days after tagging. That tag provided the first radio-relocation of a bowhead that travelled from Canadian feeding grounds west through the Alaskan Beaufort Sea. The minimum traveling **rate** of **that** whale was slow compared to rates of actively migrating bowheads determined through **theodolite** tracking over short distances, although comparable with rates revealed by previous long-distance resightings of **individually** recognizable **bowheads**. **It** is likely that the tagged whale did not travel in a straight **line**, and it 'is possible that **the slow** rate was a result of feeding stops either near the tagging location before migration began, or within the Alaskan Beaufort Sea. The minimum average traveling rates of <sup>two</sup> other tagged bowheads were also slow and may have resulted from feeding stops by those whales.

Given earlier deployment of tags, it should be possible to achieve greater success in radio monitoring of tagged bowheads. If tags were applied well before **active** migration began, it is **likely** that the feeding rates and **residence** times could be elucidated. A larger vessel than that available in 1986--one with navigational aids, a seaworthy design, and space to allow overnight activities--would be helpful by increasing time at sea.

### Literature Cited

Literature cited in this Appendix is listed in the main Literature Cited section, on p. 487-511.

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